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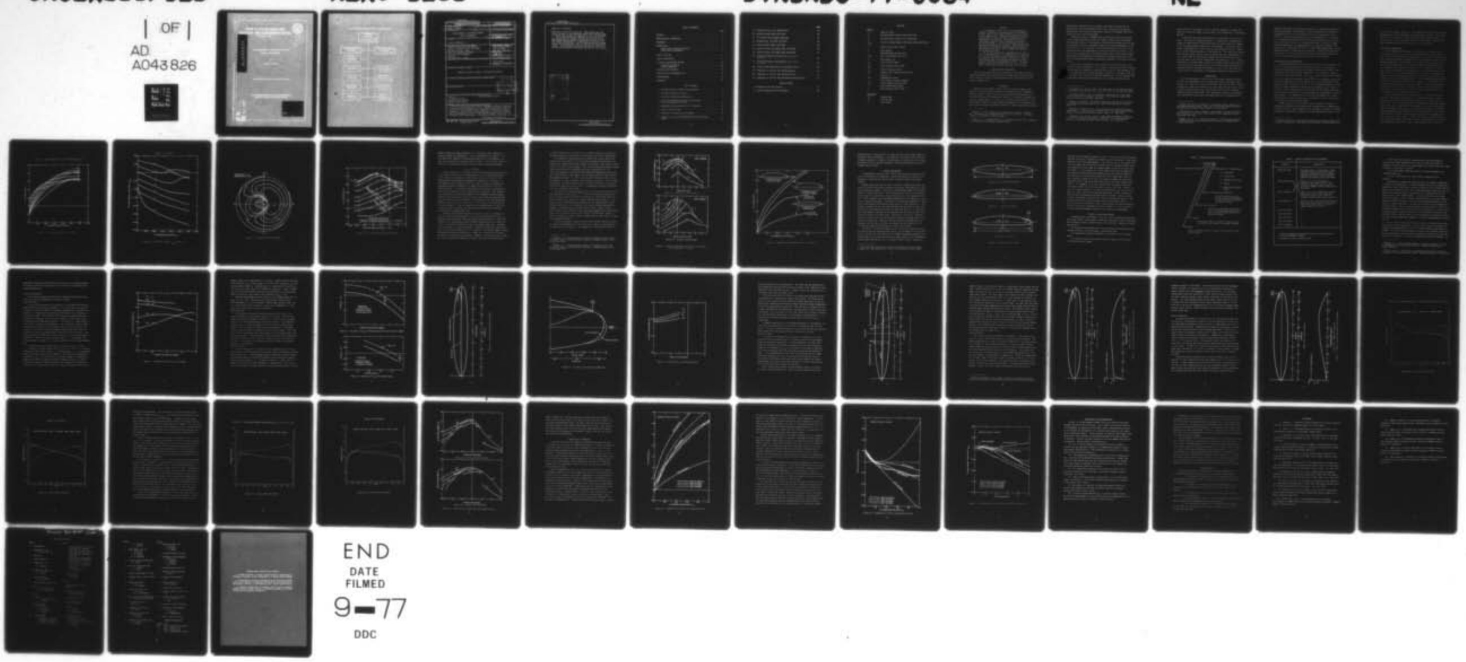

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AN ASSESSMENT OF CIRCULATION CONTROL AIRFOIL DEVELOPMENT

by

Joseph B. Wilkerson

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AVIATION AND SURFACE EFFECTS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

AN ASSESSMENT OF CIRCULATION CONTROL AIRFOIL DEVELOPMENT

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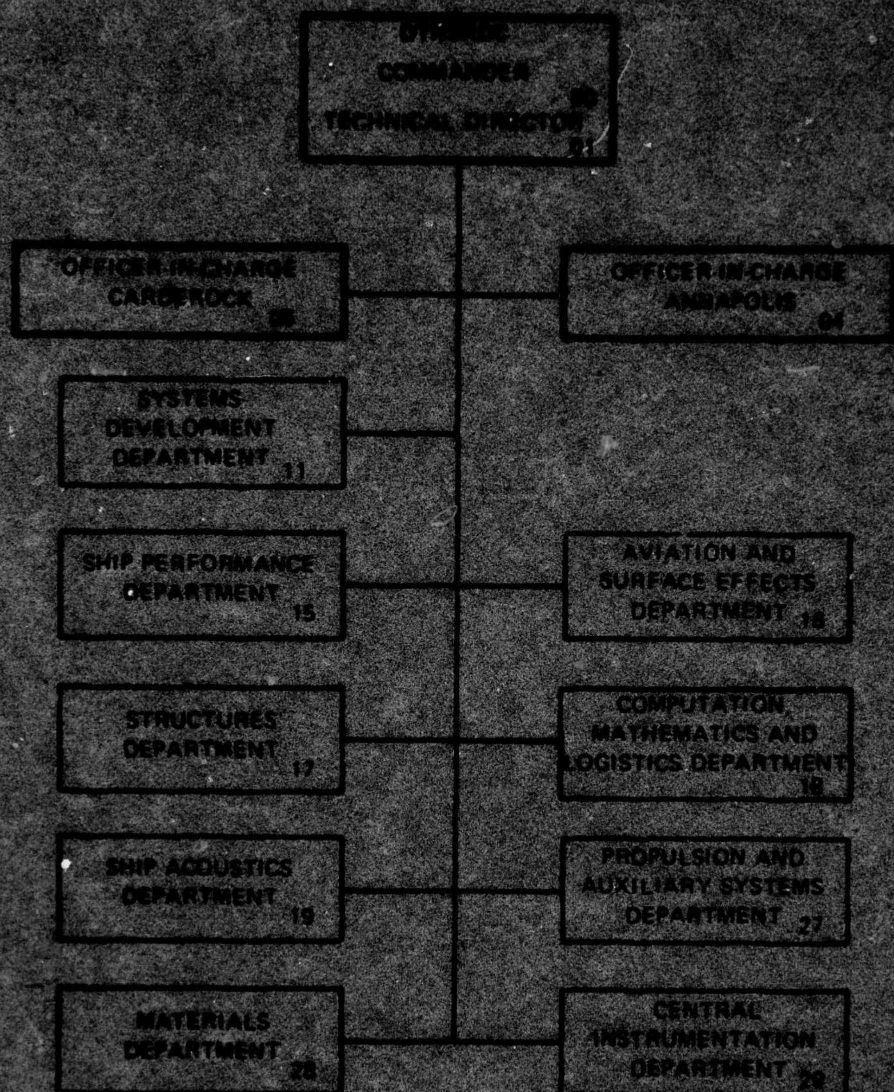

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER (19) (18) DTNSRDC 77-0084

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle) (6) AN ASSESSMENT OF CIRCULATION CONTROL AIRFOIL DEVELOPMENT

5. TYPE OF REPORT & PERIOD COVERED (9) Research and development rept. Jul 75-Sep 76,

6. PERFORMING ORG. REPORT NUMBER (14) Aero ~~Report~~-1238

7. AUTHOR(s) (10) Joseph B. Wilkerson

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
David W. Taylor Naval Ship R&D Center
Aviation & Surface Effects Department
Bethesda, Maryland 20084

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Program Element 63203N
Task Area W0578
Work Unit 1-1619-200

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Air Systems Command
AIR-320D
Washington, D.C. 20361

12. REPORT DATE (11) August 1977

13. NUMBER OF PAGES ~~55~~ (12) 53p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report) UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Airfoil
Circulation Control
Two-Dimensional Testing
Boundary Layer Control
Helicopter Blade Airfoil

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A circulation control (CC) airfoil development program is presented, including an airfoil designation system. Specific performance objectives are set forth as development goals. Background information includes an assessment of state-of-the-art design practices, a comparison of operational requirements with those of conventional airfoils, and a discussion of previous airfoil performance. Selection and design criteria are → next page

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described for five new CC airfoils. These designs were wind tunnel evaluated as two-dimensional models and a limited amount of airfoil data is shown for comparison to the prior data base.

Two of the airfoils were designed with the objective of maintaining high lift augmentation and improving the critical Mach number characteristics, a combination of qualities that was previously nonexistent. Both designs theoretically accomplished the prescribed goals and were validated by experimental results. The development program has advanced the state of the art and nearly doubled the available data base for CC airfoils.

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NOTATION

Symbols

a	Speed of sound
C_d	Two-dimensional profile drag coefficient
C_ℓ	Two-dimensional airfoil lift coefficient
$C_{m_{50}}$	Airfoil pitching moment coefficient about half-chord
C_μ	Blowing coefficient, $\dot{m}V_j/qs$
c	Chord length
ℓ	Two-dimensional airfoil lift
ℓ/d_e	Lift to equivalent drag ratio
M	Mach number, V/a
M_{cr}	Critical Mach number
M_{dd}	Drag divergence Mach number
t/c	Airfoil thickness ratio
r/c	Airfoil local radius-to-chord ratio
V	Velocity
x/c	Dimensionless chord
α	Local angle of attack, degrees
δ/c	Airfoil camber-to-chord ratio
ψ	Rotor blade azimuth angle
μ	Rotor advance ratio, $V_\infty/\Omega R$

Subscripts

ℓe	Leading edge
te	Trailing edge
∞	Free stream

ABSTRACT

A circulation control (CC) airfoil development program is presented, including an airfoil designation system. Specific performance objectives are set forth as development goals. Background information includes an assessment of state-of-the-art design practices, a comparison of operational requirements with those of conventional airfoils, and a discussion of previous airfoil performance. Selection and design criteria are described for five new CC airfoils. These designs were wind tunnel evaluated as two-dimensional models and a limited amount of airfoil data is shown for comparison to the prior data base.

Two of the airfoils were designed with the objective of maintaining high lift augmentation and improving the critical Mach number characteristics, a combination of qualities that was previously nonexistent. Both designs theoretically accomplished the prescribed goals and were validated by experimental results. The development program has advanced the state of the art and nearly doubled the available data base for CC airfoils.

ADMINISTRATIVE INFORMATION

The work presented herein was conducted for the Naval Air Systems Command (AIR-320D) under Project Element 63203N, Task Area W0578, Work Unit 1-1619-200, and was accomplished during the time period July 1975 through September 1976.

BACKGROUND

Research on circulation control (CC) type airfoils began at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) in the early 1950's. These early studies included both experimental and theoretical analyses of tangentially blown air on circular cylinders and jet flap configurations. A study of the current quasi-elliptical CC airfoils began in 1968 to further evaluate and analyze those characteristics which had been obtained by Dunham[1] and Kind.[2] These investigations proved

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[1]Dunham, J., "Circulation Control Applied To A Circular Cylinder," Nat. Gas Turbine Est. (England) Report R. 287 (Jul 1967). A complete listing of references is given on page 47.

[2]Kind, R.J., "A Proposed Method of Circulation Control," Ph.D. Dissertation, University of Cambridge, England (1967).

the high lift capability of the concept, but lacked the potential for higher speed operation because multiple slots complicated the geometry. Nevertheless, the results of application studies by Cheeseman[3] and others showed that the concept had promise.

Subsequent studies at DTNSRDC have concentrated on quasi-elliptical airfoil shapes employing circular arc camber, single slots, and rounded trailing edge contours. This series of airfoils has provided both the high lift capability and the low profile drag characteristics demanded of practical airfoils. Navy interest in the program increased as a result of application studies and experiments on model rotors with CC airfoils. This application, designated the Circulation Control Rotor (CCR), was evaluated analytically by Williams[4] and by Wilkerson[5] and showed significant potential for improving performance and reducing complexity of current helicopter rotors.

Wind-tunnel evaluations of scale model CCR's proved out many of the original concept advantages.[6,7] As a result of this model proof-of-concept, and from previous feasibility study contracts, the U.S. Navy awarded a contract in February 1975 to Kaman Aerospace Corporation to design, build, and flight test a full scale CCR technology demonstrator. An H-2 airframe with the standard engines and transmission, will be retrofitted during this

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[3]Cheeseman, I.C. and A.R. Seed, "The Application of Circulation Control by Blowing to Helicopter Rotors," J.R. Ae.S., Vol. 71, No. 848 (Jul 1966).

[4]Williams, Robert M. and R.A. Hemmerly, "Determination of the (Ideal Practical) Hover Efficiency of Circulation Control Rotors," NSRDC Technical Note AL-212, AD 902-068L (Aug 1971).

[5]Wilkerson, Joseph B., "Design and Performance Analysis of a Prototype Circulation Control Helicopter Rotor," NSRDC Technical Report ASED 290 (Mar 1973).

[6]Wilkerson, Joseph B. et al., "The Application of Circulation Control Aerodynamics to a Helicopter Rotor Model," Paper 704, 29th Annual National Forum of the American Helicopter Society, Wash., D.C. (May 1973).

[7]Wilkerson, J.B. and D.W. Linck, "A Model Rotor Performance Validation for the CCR Technology Demonstrator," Paper 902, 31st Annual National Forum of the American Helicopter Society, Wash., D.C. (May 1975).

ongoing effort to incorporate a CCR, a new air compressor to supply the blown air, and a new flight control system. The demonstrator is designated XH2/CCR.

A high-speed helicopter application of CC technology is also in progress. This vehicle, designed X-Wing, is a stopped-rotor configuration capable of high subsonic flight speeds when the rotor blades are stopped in the 45-degree position relative to the fuselage. As with the conventional speed range CCR, control functions are provided by cyclic, collective, or differential modulation of the blown air. The X-Wing uses special dual blowing, double ended CC airfoils which allow lift augmentation, and lift control when the relative wind approaches from either the airfoil trailing edge of the airfoil leading edge (see References 8, 9). Lockheed-California is currently under contract to evaluate concept feasibility and to perform basic preliminary design of this advanced high speed vehicle. Additional reports and outside references on much of the above material may be found in a comprehensive bibliography compiled by Englar et al.[10]

INTRODUCTION

Initial development of the CC airfoil was mainly concerned with obtaining a good augmentation from blowing with smooth, predictable characteristics. These early efforts established the basis for later airfoils as empirical limits were obtained for a slot height-to-chord ratio, trailing edge radius-to-chord ratio, and chordwise slot location. However, comparisons between early model rotor experimental results and predicted rotor performance (using these two-dimensional airfoil characteristics)

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[8] Reader, K.R. and J.B. Wilkerson, "Circulation Control Applied To A High Speed Helicopter Rotor," Paper 1003, 32nd Annual National Forum of the American Helicopter Society, Wash., D.C. (May 1976).

[9] Williams, R.M. et al., "X-Wing: A New Concept In Rotary Wing VTOL," Paper presented at the American Helicopter Society Symposium on Rotor Technology (Aug 1976).

[10] Englar, R.J. et al., "Circulation Control - An Updated Bibliography of DTNSRDC Research and Selected Outside References," DTNSRDC Report 77-0076 (Aug 1976).

indicated that additional terms were needed for a complete description of airfoil performance. Specifically, it was realized that the effects of compressibility on lift and drag had to be better represented for the airfoils. Drag divergence points had to be represented for the various α, C_μ combinations which these airfoil sections encountered on the rotor blade. The specific effect of trailing edge radius-to-chord, or other trailing edge geometry on compressibility was largely an unknown. The initiation of contractual work for full scale flight demonstrator aircraft demanded answers to these and other questions. Although the basic characteristics of CC airfoils and the rotor applications were understood, there were many specific effects which had not been resolved.

ROTOR AIRFOIL DESIGN OBJECTIVES

Considerable emphasis has been put on the design of conventional airfoils for specific application to helicopter rotors. Both Sikorsky Aircraft and Boeing-Vertol have had programs to develop new airfoils designed especially for helicopter application. The problem is complex, involving a three-point design: high $C_{\ell_{max}}$ at low-to-moderate Mach numbers for the retreating blade azimuth region, high ℓ/d at moderate-to-high subsonic Mach numbers for the blade midspan and for the fore-and-aft blade azimuth regions, and high M_{cr} at low C_ℓ for the advancing blade tip. Sensitivity studies performed to assess rotor performance payoff to many of the basic airfoil characteristics have shown that these three characteristics are most important to rotor performance and consequently to vehicle gross weight.[11] The magnitude of airfoil pitching moment was a fourth characteristic of main concern since it determines control loads and thus can increase the control system weight.

Design objectives for CC airfoils are very similar to those for conventional airfoils with the additional considerations of augmentation, jet thrust recovery, and avoidance of jet detachment. However, CC airfoil aerodynamic characteristics depend on the two independent variables α and

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[11] Paglino, Vincent M., "The Potential Benefits of Advanced Airfoils for Helicopter Applications," SER-50858, Contract N00019-73-C-0225 (Mar 1974).

C_μ as shown in Figures 1a and 1b. This complicates analysis since a given parameter, say M_{cr}, now depends on two independent variables rather than one for each C_ℓ condition. Although there are reasonable limits to the range of each of these variables, analysis or data must be generated for many combinations in order to evaluate airfoil performance.

OPERATIONAL REQUIREMENTS

Cyclic modulation of blown air is used on a CCR system in lieu of conventional cyclic pitch to control rotor moments for trim and maneuver. Most helicopter rotor systems, including CCR, require that lift conditions near the advancing blade tip approach zero or even negative values as the maximum forward speed is approached. Roll moment trim requirements and the increasing magnitudes of lift being developed by inboard portions of the advancing blade produce the negative effect. However, the CCR must also retain some blowing on the advancing blade to allow for cyclic pneumatic control. Thus, the operational angle of attack at the advancing blade tip must be sufficiently negative to cancel out positive lift contributions from both blowing and camber. This condition basically establishes the rotor system collective pitch setting. In combination with inflow conditions then, the operational angle of attack over the rest of the disk is also determined. Pneumatic blowing control is then superimposed over this flow field to obtain the desired distribution of lift coefficients for rotor moment trim conditions.

The described operational requirements for a CCR airfoil are quite different from those of an airfoil for a conventional rotor. Figure 2 shows a typical distribution of blade section angle of attack over the rotor disk. It is first noted that these distributions represent trimmed flight conditions and have very little similarity to their conventional rotor counterparts. Not only are the angles quite negative but the conventional angle-of-attack increase on the retreating side of the disk is totally absent. This is a direct result of using cyclic blowing rather than cyclic pitch trim control. Typical combinations of blade section C_ℓ and α around the azimuth are shown in Figure 3, superimposed on a plot of two-dimensional airfoil data. High C_ℓ requirements occur at the more

Figure 1 — Two-Dimensional CC Airfoil Characteristics

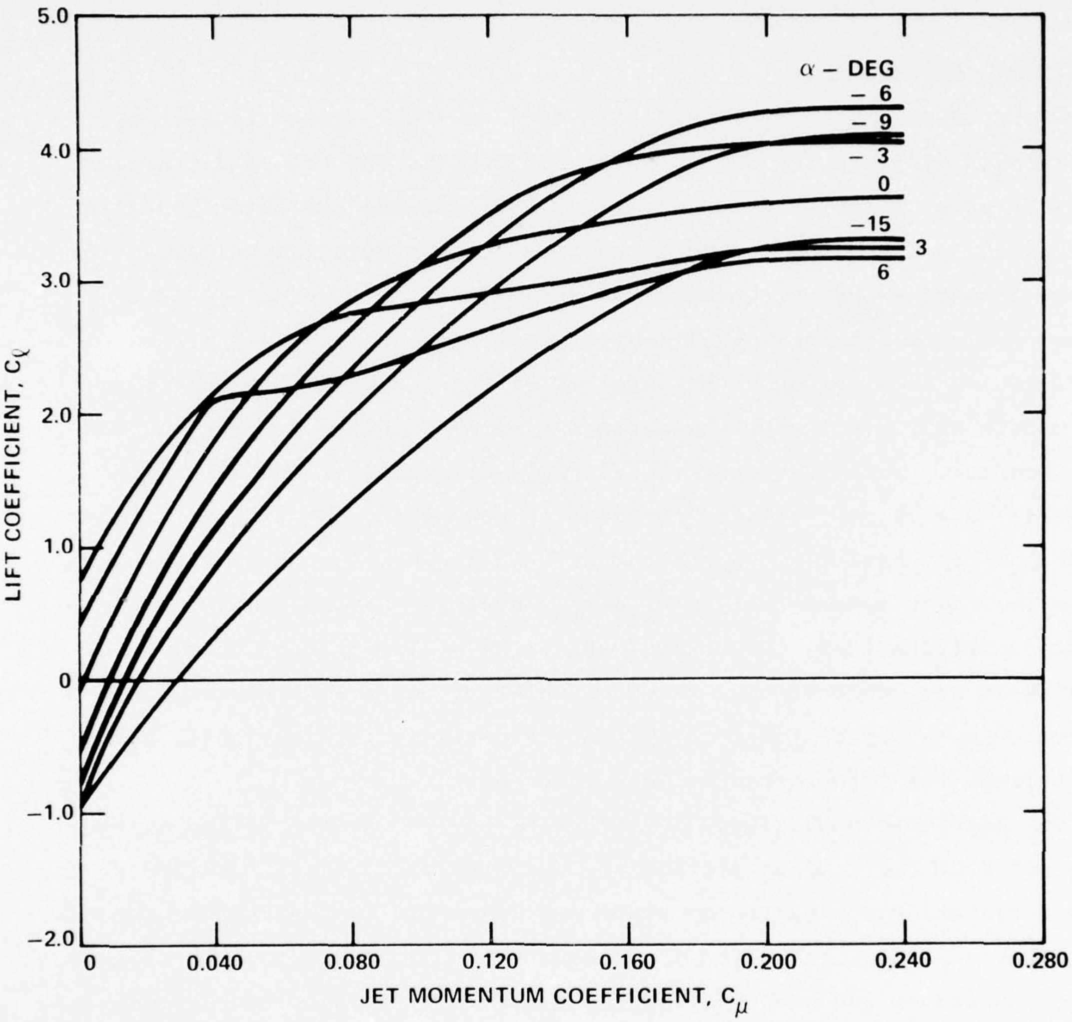

Figure 1a - 15-Percent Ellipse, C_ℓ versus C_μ

Figure 1 (Continued)

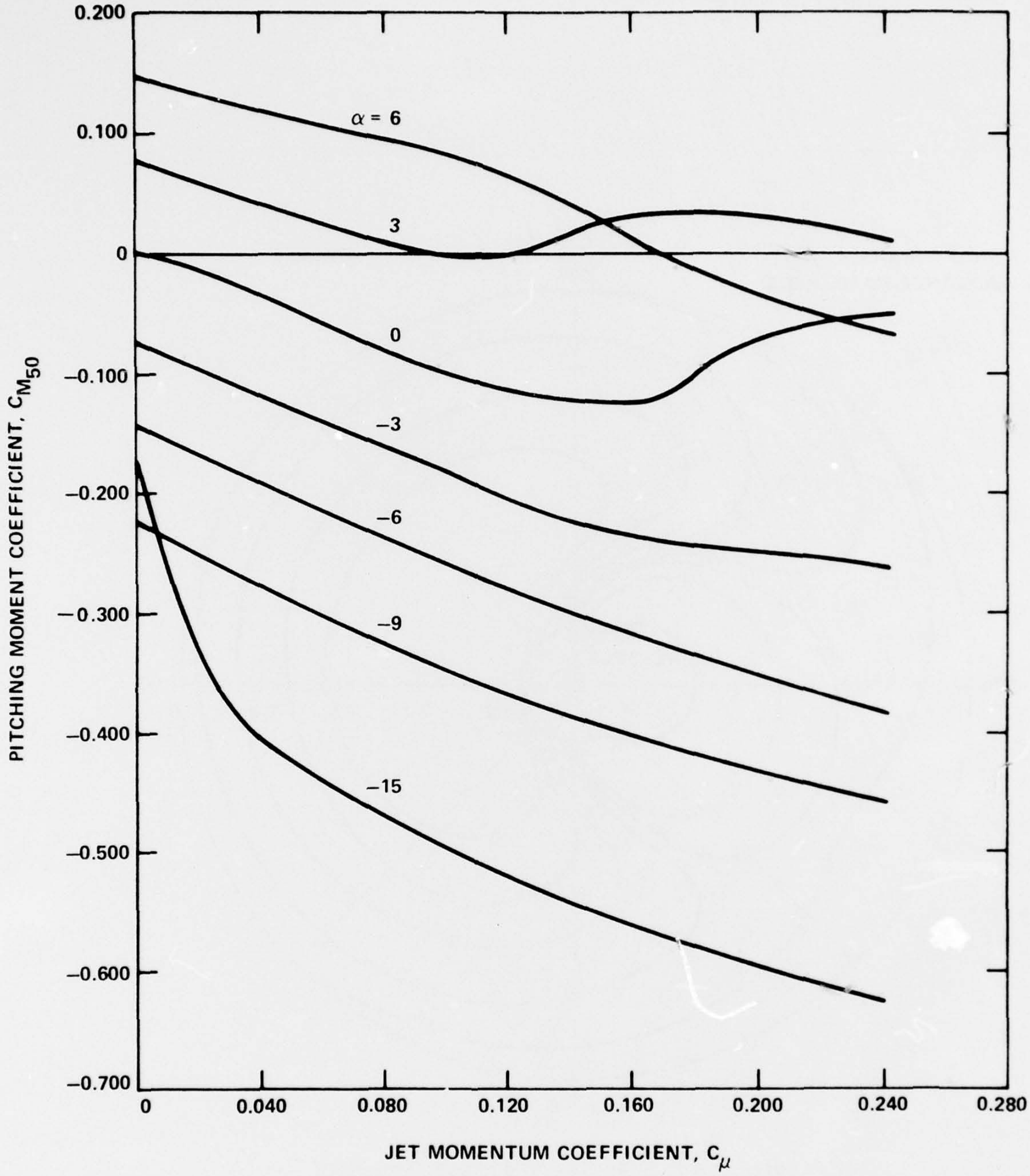

Figure 1b - 15-Percent Ellipse, $C_{m_{50}}$ versus C_μ

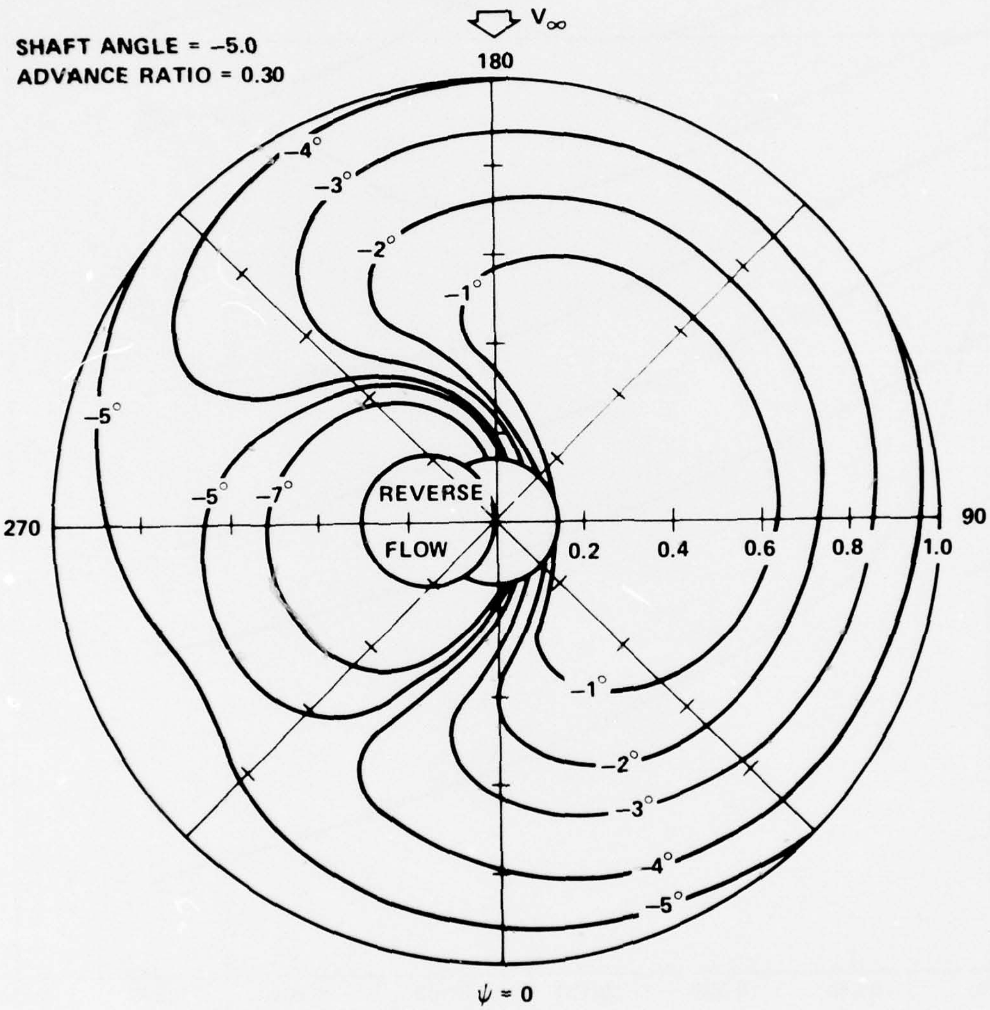

Figure 2 — CCR Angle-of-Attack Contours

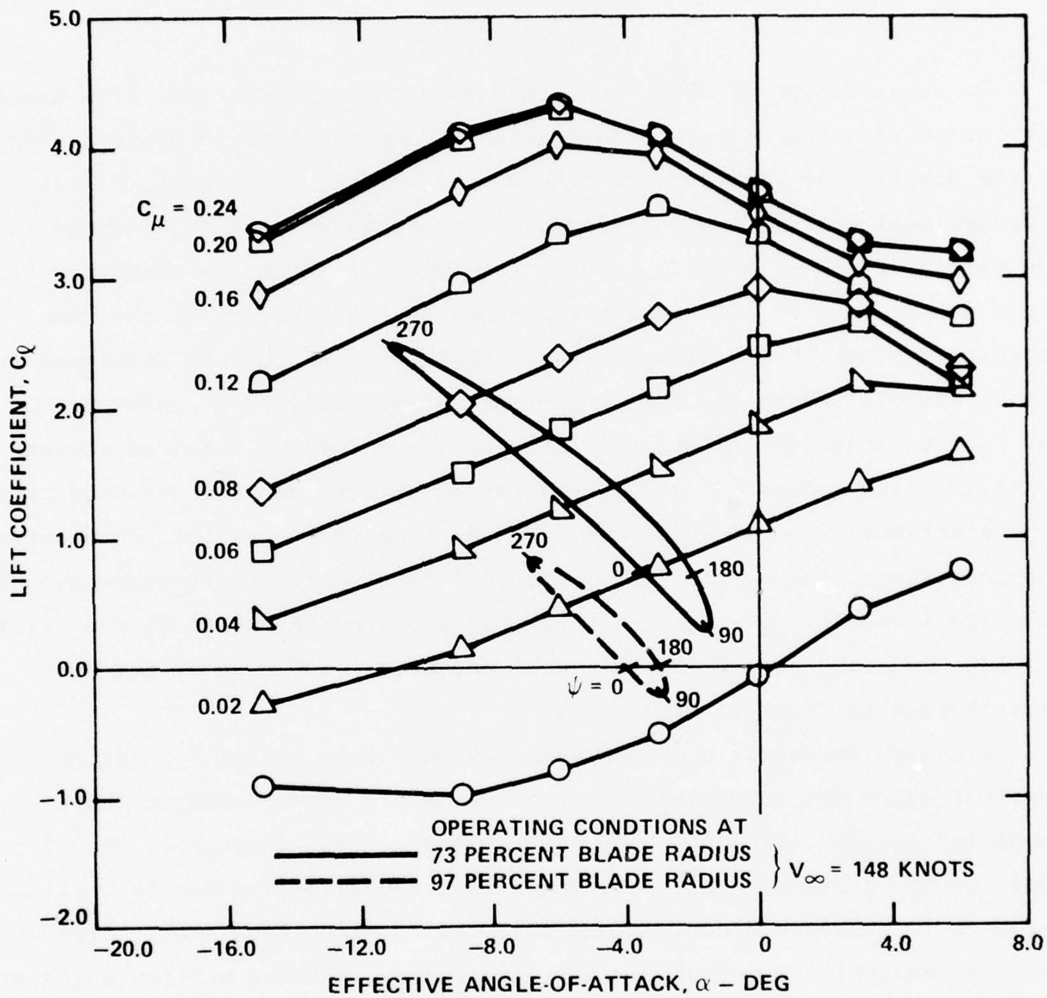

Figure 3 — CC Airfoil Operational Conditions

negative angle-of-attack conditions (ψ = 270 degrees) which demands increased blowing for compensation. Low C_ℓ requirements are compatible with the higher Mach numbers at the advancing blade tip (ψ = 90 degrees), but they are by necessity at negative angle of attack. These are the conditions which the CC airfoil must operate in and to which it must be designed.

STATE OF THE ART

To date, design of CC airfoils has been through potential flow analysis with standard corrections for compressible flow and through observations of the behavior of previous two-dimensional airfoil wind tunnel models. (Conventional airfoil analysis programs by themselves are impractical in the design of the CC airfoil, since they cannot analyze the rounded trailing edge and have no allowance for changes in the position of the rear stagnation point. Such analysis and design routines must be developed for the CC airfoil before its full potential can be realized.) This approach has considerable justification because of the agreement obtained between potential flow around the quasi-elliptical sections and the measured pressure distribution on airfoil models. This comparison has been documented numerous times, and may be found in any of the reports on two-dimensional CC airfoil models. It may be argued that the blowing energy at the trailing edge induces, or allows, the ideal potential flow type of pressure distribution in incompressible flow.

Although potential flow analysis has been very useful for design, it does not allow any determination of the C_μ which corresponds to the C_ℓ, α condition being analyzed. Other limitations are the absence of drag determination and a questionable pitching moment determination due to small differences in pressure distributions near the trailing edge slot. Although not yet available, a computer program is currently being written which will have full analytical capability for CC airfoils. The program CIRCON is being developed by Analytical Methods, Inc., under Navy contract with technical monitoring and consultation provided by DTNSRDC. The routine includes boundary layer calculations, separation criteria, and wall jet representation

to allow evaluation of the specific relationship between airfoil geometry (trailing edge and slot geometry in particular) and airfoil augmentation.

The contours of two-dimensional CC airfoil wind tunnel models have historically been limited to (1) elliptical thickness distributions, (2) circular arc camber with maximum camber at 50-percent chord, and (3) elliptical or circular trailing edges. Prior to the present development program, these airfoils served to establish essential characteristics. To cite a few examples, the airfoils have exhibited augmentation ratios over 50, ℓ/d_e values up to 100, almost full jet thrust recovery, and critical Mach numbers beyond 0.75. This is an especially impressive list of characteristics for such a severely limited family of profiles. But, as might be expected, all these characteristics were not exhibited by a single airfoil, nor do they all occur at the α, C_μ combination required for application to a helicopter rotor blade.

Two airfoils in particular have shown the tradeoff between obtaining good augmentation and good M_{cr}.[12,13] Wind tunnel evaluation showed that for a 15-percent-thick CC airfoil, an elliptical trailing edge gave much better values of M_{cr} than did a circular trailing edge (Figure 4). Also, the elliptical trailing edge provided better lift augmentation at high subsonic speeds ($M_\infty \geq 0.5$); however, the circular trailing edge was far superior in augmentation for incompressible flow as shown in Figure 5. Still another two airfoils have shown low speed augmentations which exceed that of the 15-percent-airfoil with circular trailing edge. Figure 5 shows a comparison of these airfoils' augmentation at zero angle of attack for incompressible flow.

As with any design, tradeoffs must be made between previous airfoils to obtain high augmentation at low speed versus high M_{cr} characteristics, or high ℓ/d_e versus high M_{cr}. The designer of a CCR must use the best

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[12] Englar, R.J., "Two-Dimensional Transonic Wind-Tunnel Tests of Three 15-Percent Thick Circulation Control Airfoils," DTNSRDC Technical Note AL-182 (Dec 1970).

[13] Englar, R.J., "Two-Dimensional Subsonic Wind-Tunnel Tests of Two 15-Percent Thick Circulation Control Airfoils," DTNSRDC Technical Note AL-211 (Aug 1971).

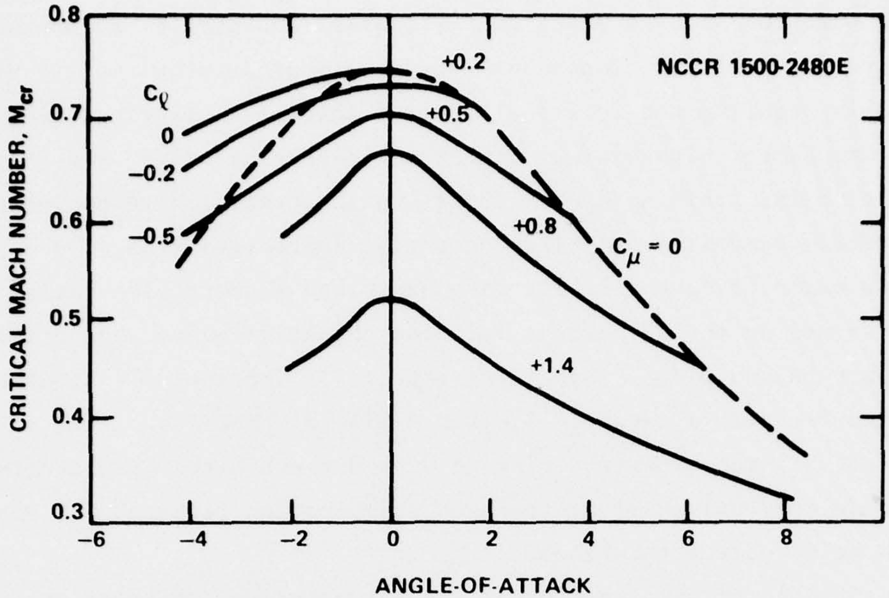

Figure 4a - Elliptical Trailing Edge

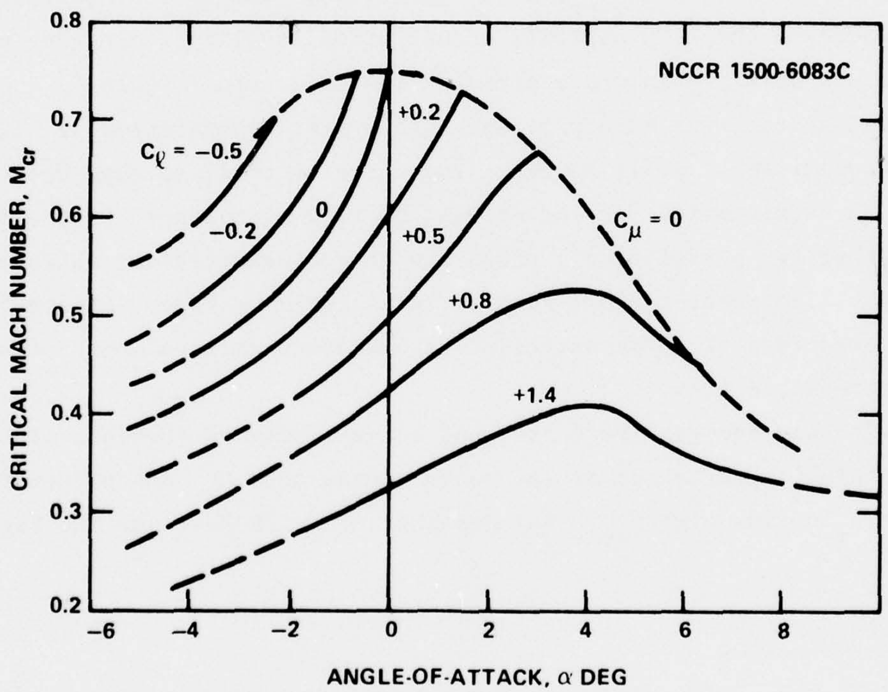

Figure 4b - Circular Trailing Edge

Figure 4 — Critical Mach Number Variation of 15-Percent Thick Uncambered CC Airfoils

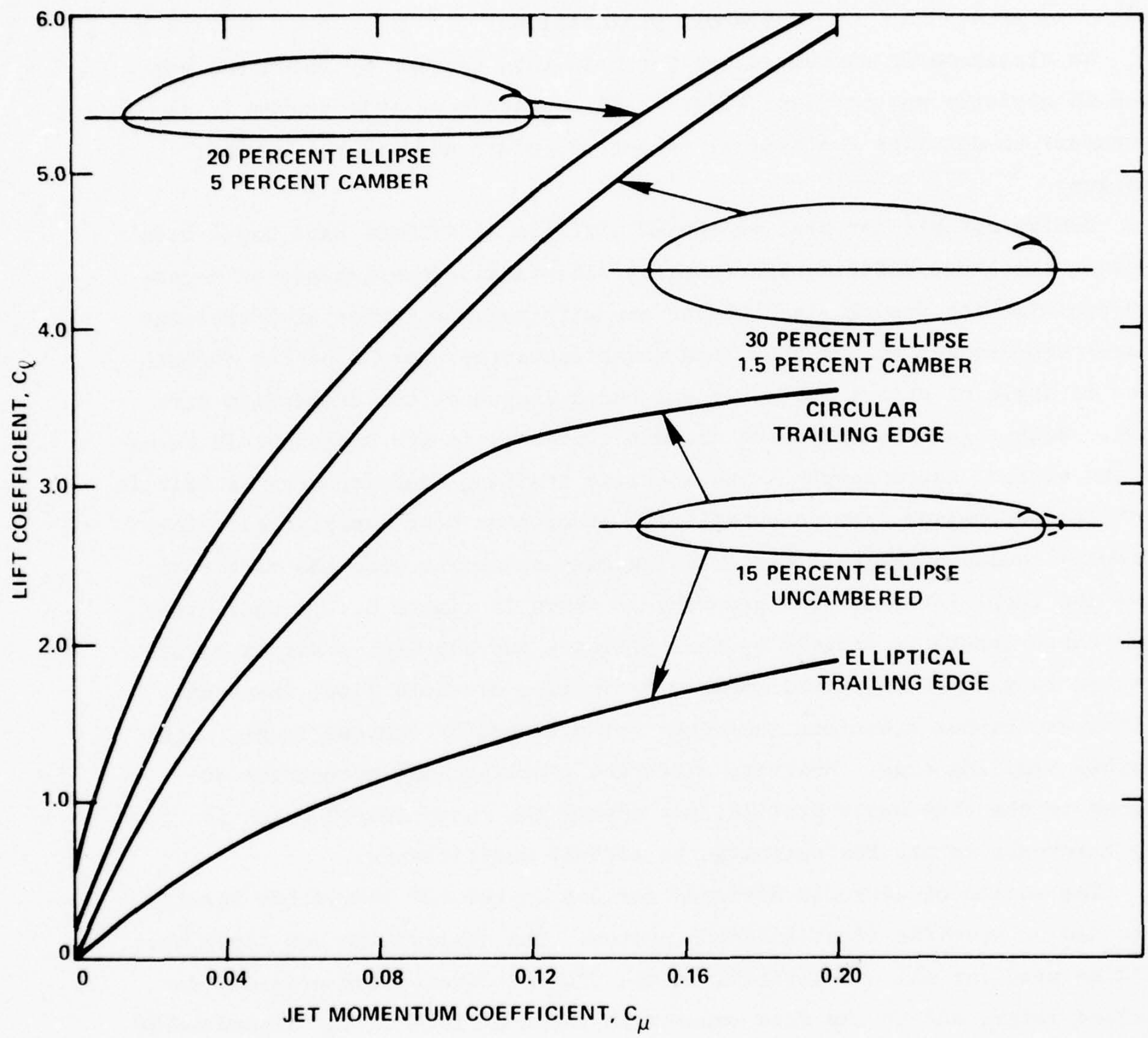

Figure 5 — Augmentation Characteristics of CC Airfoils

characteristics of each airfoil to obtain the best rotor design within the available airfoil performance. The purpose of the present CC airfoil development program is to improve the performance of these airfoils, thereby decreasing the rotor design compromises and increasing overall rotor performance and efficiency.

AIRFOIL DESIGNATION

An alphanumeric system is set forth in this section by which the various CC airfoils may be identified. Before describing this system it is necessary to describe the typical layout procedure used in the airfoil designs.

Design layouts for most of the CC airfoils at DTNSRDC have begun with a basic thickness distribution (usually elliptical) superimposed on a camber distribution (usually a circular arc with maximum camber at 50-percent chord) see Figures 6a and 6b. This establishes the chord line for definition of angle of attack and a virtual chord length of the unmodified airfoil. Both thickness ratio and maximum camber ratio are expressed in terms of the virtual chord length. The specific trailing edge geometry is laid in next (as determined from potential flow studies or past experience). This geometry includes not only the trailing edge shape but also the slot position and local internal slot geometry as shown in Figure 6c. Actual airfoil chord length is defined by this geometry and the slot position is described in percent of actual chord. Definition of chord line, thickness ratio, and camber ratio are therefore not affected by changes local to the airfoil trailing edge. However, different trailing edge geometries designed to the same basic profile, may change the chord length which is the reference length for defining the airfoil coefficients.

The series of airfoils designed for use on the CCR system has heretofore had no specific identification system. The designation set forth here will be used for all CCR airfoils in the DTNSRDC development program, described later, and in the data reports on those airfoils. The alphanumeric system begins with NCCR for Navy Circulation Control Rotor* followed by

*The rotor identification is to allow a distinction from CC airfoils designed for other applications, such as the Circulation Control Wing.

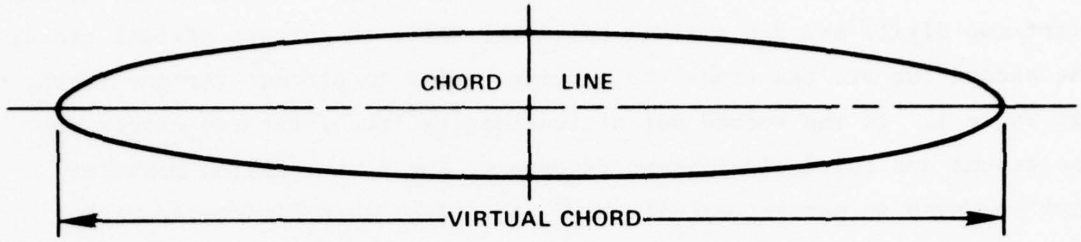

Figure 6a - Thickness Distribution

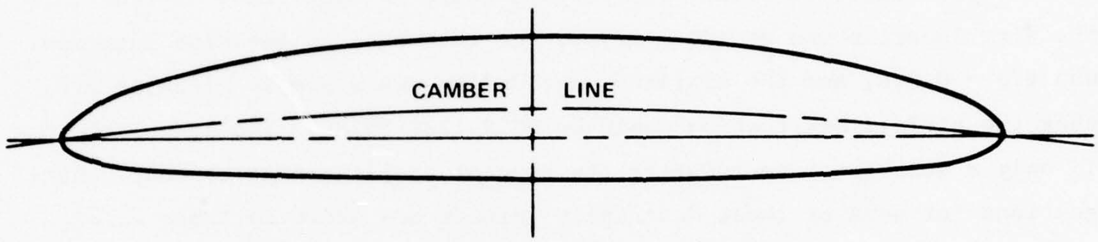

Figure 6b - Thickness and Camber

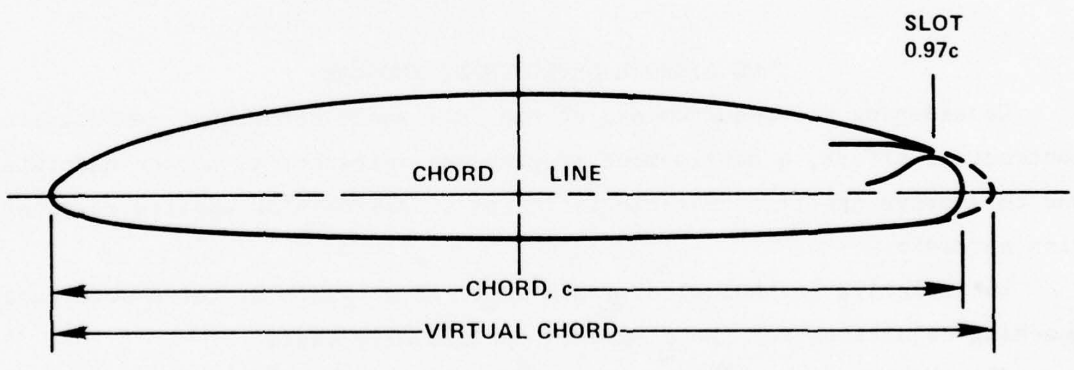

Figure 6c - CC Airfoil

Figure 6 — Typical Airfoil Layout

two sets of four digits followed by a letter. The first set of four digits describe the airfoil thickness and camber, and the second set of four digits describe the trailing edge geometry. In the first set of four digits, the first two digits are the airfoil thickness ratio in percent virtual chord; the second two are ten times the maximum camber in percent virtual chord, see Table 1. In the second set of four digits, the first two digits are the second and third significant figures of the slot location measured from the nose in percent actual chord (the first significant figure for slot location is taken to be 0.9); the second two digits are the airfoil thickness ratio in percent actual chord taken at the slot location, see Table 1. For example, if the basic profile were 12-percent thick with 3.4-percent camber the first four digits would be NCCR 1234. Further, if the slot location was at $x/c = 0.956$, the thickness at the slot location was $t/c = 0.078$, and the trailing edge design was a simple circular arc, then the airfoil designation would be NCCR 1234-5678C. The last letter is only a descriptor to identify the type of trailing edge contour. Suggestions for some of these descriptor letters are shown in Table 1. A cross reference is provided in Table 2 which applies the above designation system to previously documented CC airfoil contours. The five airfoils of the current development program are also listed for completeness.

CC AIRFOIL DEVELOPMENT PROGRAM

Considering the requirements of the full scale technology demonstrator contractual effort, a development program was initiated to better understand and to improve specific characteristics of CC airfoils as applied to rotary wing aircraft.

The relative technological youth of these airfoils dictated some long reaching objectives for the program. Specifically that:

(1) augmentation should be improved by 20 percent in the low speed range,

(2) equivalent lift-to-drag ratio should be improved by 40 percent in the moderate speed range,

TABLE 1 – DESIGNATION FOR CCR AIRFOILS

NCCR 1516-7464N

Navy Circulation Control Rotor

Descriptor for Coanda Surface

E – elliptical

C – circular arc

N – nominal circular arc

S – spiral

D – dual blowing (double ended)

Trailing Edge Bluffness:

Airfoil thickness ratio in percent actual chord measured at slot location (6.4-percent thickness as shown)

Slot Location:

This is the second and third digit of the slot location measured from the nose in percent actual chord (97.4 percent as shown)

Camber:

The maximum camber in percent virtual chord is one-tenth of this value (1.6 percent as shown)

Thickness:

Airfoil thickness ratio in percent virtual chord (15 percent as shown)

TABLE 2 — AIRFOIL DESIGNATION CROSS REFERENCE

AIRFOIL	PUBLICATION
NCCR 2050-7395C	Williams, Robert M. and Harvey J. Howe, "Two-Dimensional Subsonic Wind Tunnel Tests on a 20-Percent Thick, 5-Percent Cambered Circulation Control Airfoil," NSRDC Technical Note AL-176 (Aug 1970).
NCCR 1500-2480E	Englar, R.J., "Two-Dimensional Transonic Wind Tunnel Tests of Three 15-Percent Thick Circulation Control Airfoils," DTNSRDC Technical Note AL-182 (Dec 1970).
NCCR 1500-6083C	Englar, R.J., "Two-Dimensional Subsonic Wind Tunnel Tests of Two 15-Percent Thick Circulation Control Airfoils," DTNSRDC Technical Note AL-211 (Aug 1971).
NCCR 2000-7271C	Abramson, Jane, "Two-Dimensional Subsonic Wind Tunnel Evaluation of a 20-Percent Thick Circulation Control Airfoil," DTNSRDC ASED-331 (Jun 1975).
NCCR 1510-7067N	*
NCCR 1510-7567S	*
NCCR 1505-7567S	*
NCCR 1513-7559E	*
NCCR 1610-8054S	**

* Airfoils designed and evaluated subsonically during current airfoil development program.

** Performed transonic evaluation also.

(3) at least one airfoil be designed which would give both (a) critical Mach number characteristics similar to the pure ellipse in transonic operation and (b) low speed augmentation characteristics at least equivalent to previous CC airfoils,

(4) pitching moment magnitudes should be reduced throughout the operating range, and

(5) lift characteristics at high subsonic speeds should be improved.

The approach to accomplish these objectives is through a combination of analysis and experiments. It became evident early in the program that objectives 1 and 2 would have to await availability of the CIRCON analysis. While several hypotheses exist for accomplishing these objectives, the necessary fine tuning can only be carried out by a sophisticated computer analysis such as the CIRCON program. The other objectives were sought after by two means. First, selective perturbations on CC airfoil designs which were within the realm of previous data allowed experimental verification of certain hypotheses. Second, two CC airfoils were designed without restrictions. That is, these designs were not required to have basic elliptical thickness distributions, circular arc camber, or circular trailing edge geometry. While the design tool was essentially potential flow analysis, earlier work had shown that the program gave reasonable estimates for critical Mach number when compared to transonic two-dimensional airfoil data.[14]

Five CC airfoils resulted from this procedure: three from the selection process and two new designs. Each of these airfoils was modeled and evaluated two-dimensionally in the 15- x 20-inch Subsonic Wind Tunnel at DTNSRDC. One of the two new designs was selected for transonic evaluation. This two-dimensional airfoil model was designed and manufactured (see Reference 15) to span the 7- x 10-foot Transonic Wind Tunnel at DTNSRDC. The

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[14] Rogers, E.O., "Critical Mach Numbers of Circulation Control Airfoils as Determined by Finite-Difference Methods," DTNSRDC Technical Note AL-273 (Aug 1972).

[15] Clark, Albert P., "Design Of A Circulation Control Airfoil Model for Evaluation In the Transonic Wind Tunnel," DTNSRDC CID Report 77-1 (Mar 1977).

wind-tunnel evaluation provided data for varying α, C_μ, and Mach numbers. The model chord was 18 inches which is full scale for the XH2/CCR Technology Demonstrator.

SELECTION AND DESIGN

This section outlines the selection or design process which led to each of the five two-dimensional CC airfoil contours.

NCCR 1510-7067N:

This airfoil was chosen for the blade tip of the XH2/CCR Technology Demonstrator after analytical tradeoffs. It is well within the contour variations of prior CC airfoils to maintain minimum risk. Basically, the profile is a 15-percent-thick elliptical distribution with one-percent circular arc camber. The thickness of 15 percent was maintained since it represents the thinnest section for which there is existing data (both incompressible and high speed subsonic). The addition of camber was desired since it enhances CC augmentation. The circular arc type of camber distribution was chosen to be consistent with the prior data base, and because it was known to avoid any sudden pressure peaks and it does not contribute to airfoil pitching moment (about the 50-percent chord). One-percent camber was chosen from predicted values of M_{cr} at several camber magnitudes. Figure 7 shows M_{cr} variations with C_ℓ, α combinations for four magnitudes of camber on a 15-percent ellipse with a circular trailing edge.

The addition of some camber tends to improve M_{cr} for $C_\ell = +0.25$, $\alpha = -4$ degrees, with minor reductions to M_{cr} at $C_\ell = -0.10$, $\alpha = -2$ degrees. Applying the variations of Figure 7 to the operating C_ℓ, α at the advancing blade tip provides a more direct tradeoff. This was done by generating trimmed rotor C_ℓ, α for each of the tip cambers assumed. (Changing tip camber on the CCR, at constant collective blowing, results in a slight compensating change in collective pitch. This changes the relative contributions to C_ℓ from camber, angle of attack, and blowing, which gives a

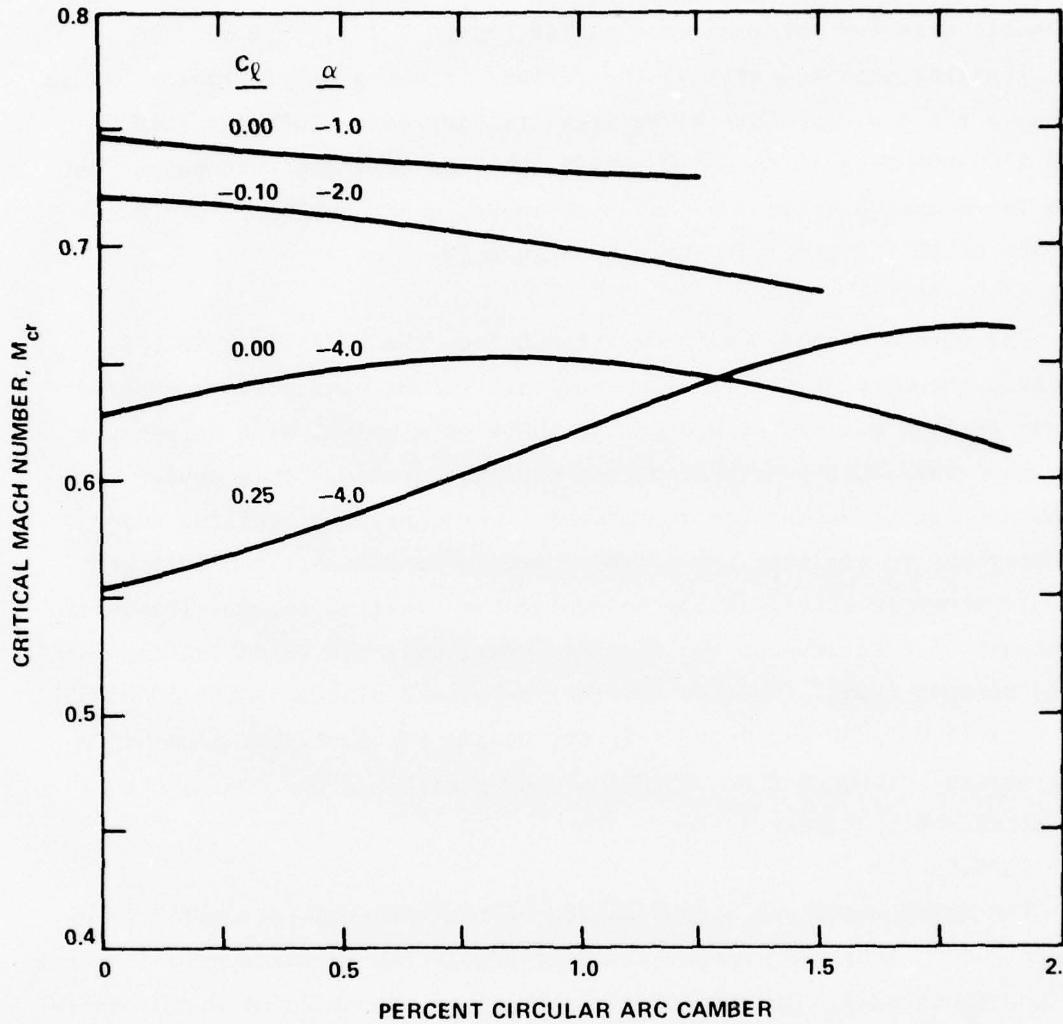

Figure 7 — Variation of Airfoil M_{cr} with Camber

slight change in the operating net C_ℓ as well.) Figure 8 shows the resultant variation of M_{cr} versus camber as the difference between M_{cr} and the operating Mach number M_∞. Assuming M_{DD} is a conservative 0.05 above M_{cr}, the one-percent camber will still avoid drag divergence. Figure 9 shows that the one-percent camber will avoid drag divergence on the advancing blade tip even for rotor advance ratios beyond $V_\infty/V_{TIP} = 0.40$.

Trailing edge geometry of the airfoil is not a simple radius but is close to r/c = 0.03. This gives less trailing edge bluffness than NCCR 1500-6083C so as to avoid sudden trailing edge pressure peaks, but is a large enough effective radius to ensure good augmentation. Outer contour of this airfoil is shown in Figure 10.

NCCR 1510-7567S:

The second airfoil profile differed from the first only in the specific geometry of the trailing edge aft of the slot. The so-called Coanda surface was redesigned to the shape of a spiral with increasing radius of curvature progressing from the slot around. This design perturbation was to assess the importance of the specific trailing edge geometry and to evaluate the spiral shape in particular. An enlarged view is shown in Figure 11 comparing the two trailing edges. It was the first set of data between two airfoils where only the Coanda surface differed between them. (The two earlier 15-percent models, NCCR 1500-2480E and NCCR 1500-6083C had very different Coanda surfaces, but also had a four-percent difference in chordwise slot position which contributed to performance differences.)

NCCR 1505-7567S:

The third model was a combination of the cambered rear half of the second model, including spiral trailing edge, with an uncambered 15-percent ellipse front half. This seemingly unlikely combination of mixed camber was selected because it had been predicted to have surprisingly good M_{cr} values over the range of C_ℓ, α as shown in Figure 12. Again, the aft camber was desirable for its enhancement to augmentation. Also, the aft half of the model was already available (from the previous model), so only

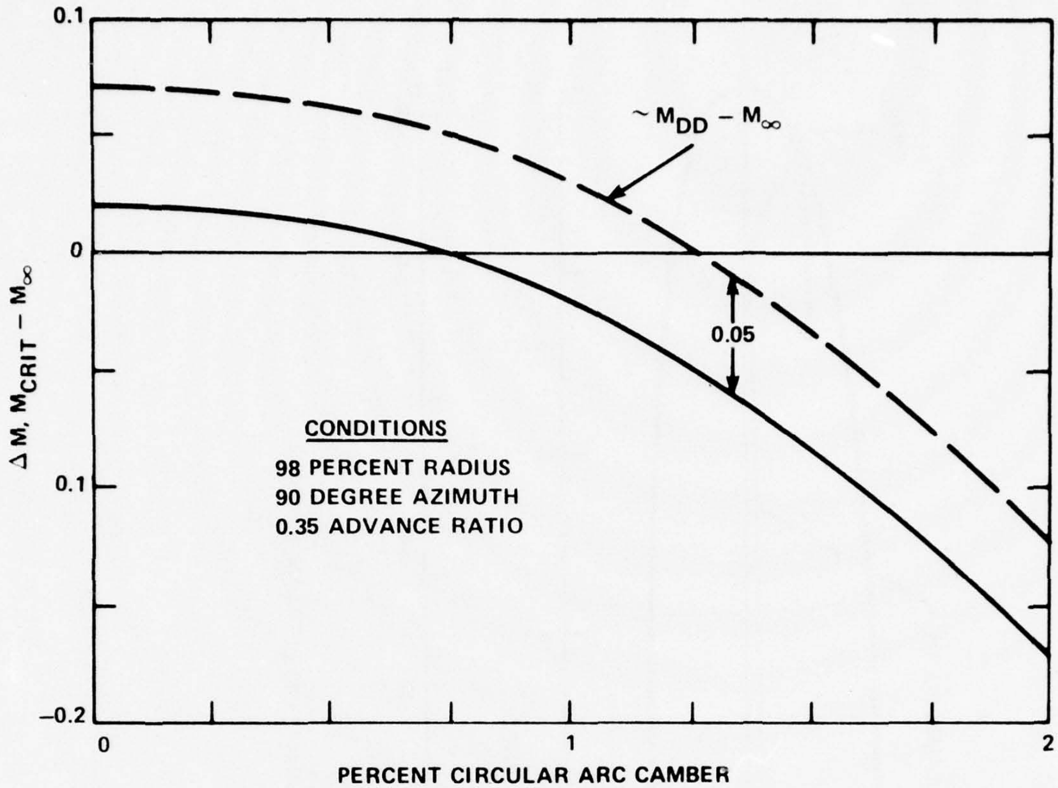

Figure 8 - Variation of M_{cr} at Advancing Blade Tip with Airfoil Camber

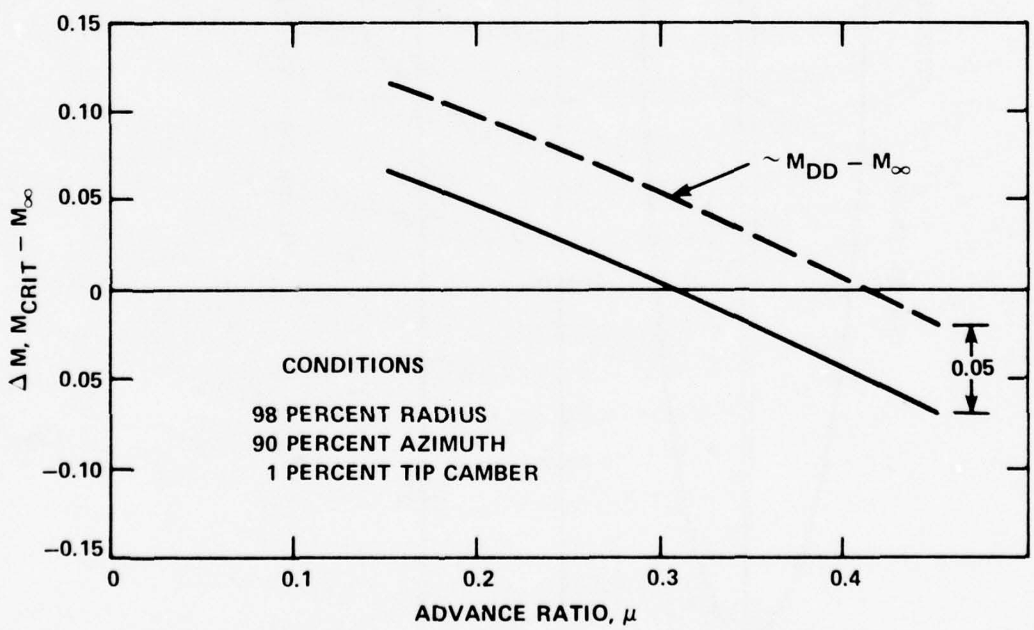

Figure 9 - Variation of M_{cr} with Advance Ratio

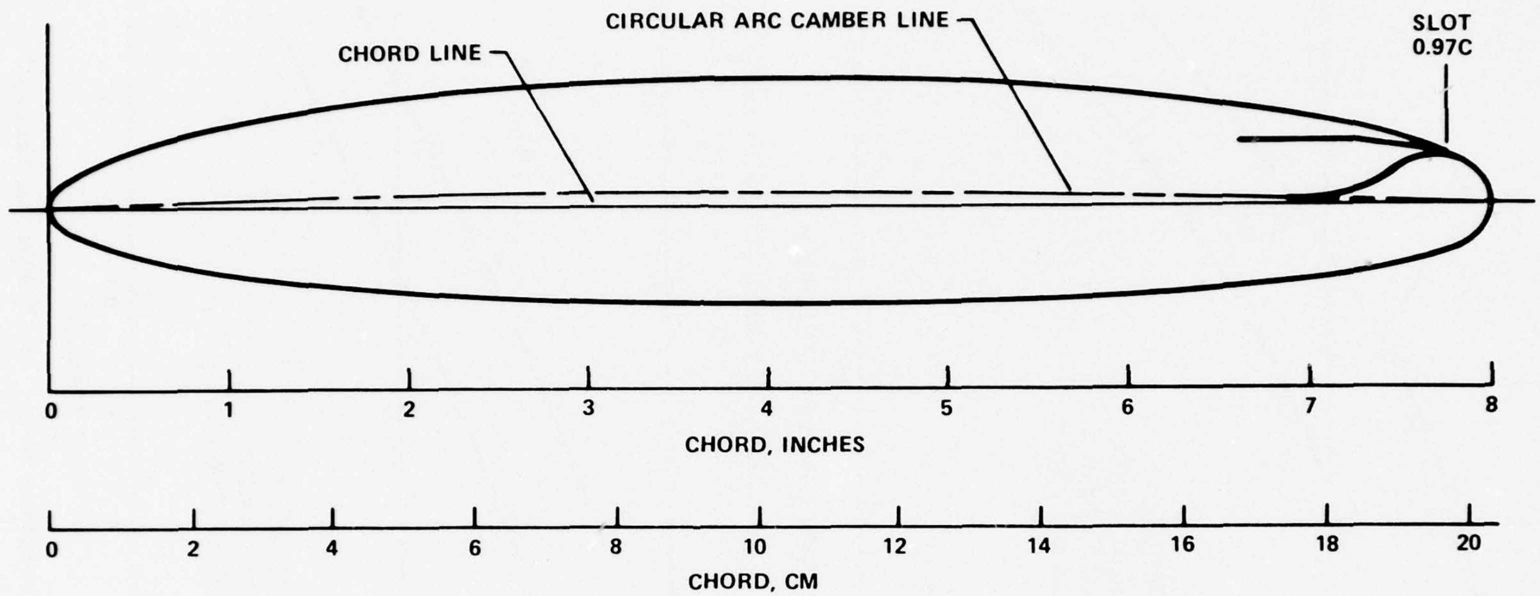

Figure 10 — Airfoil Contour NCCR 1510-7067N

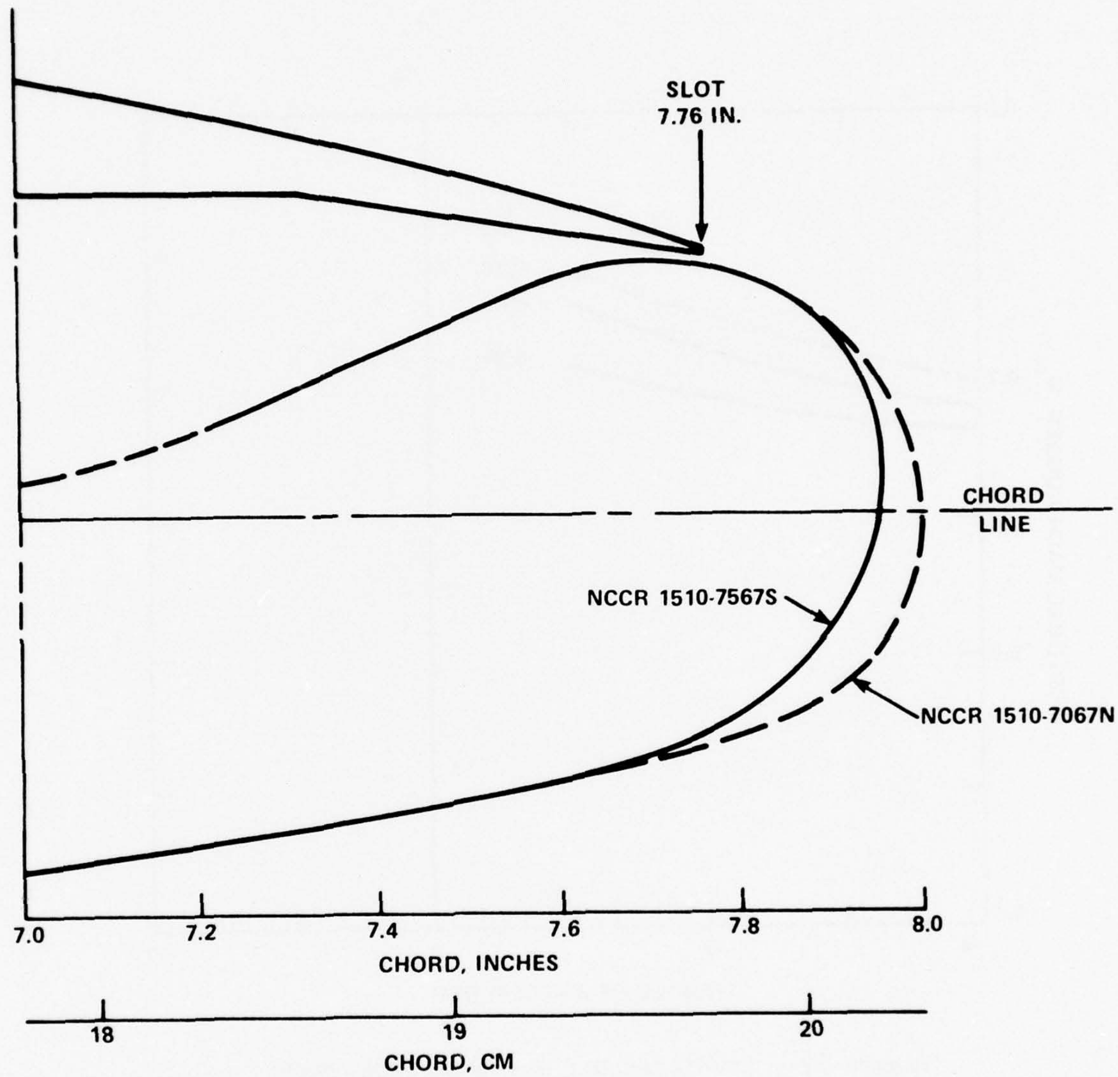

Figure 11 — CC Airfoil Trailing Edge Comparison

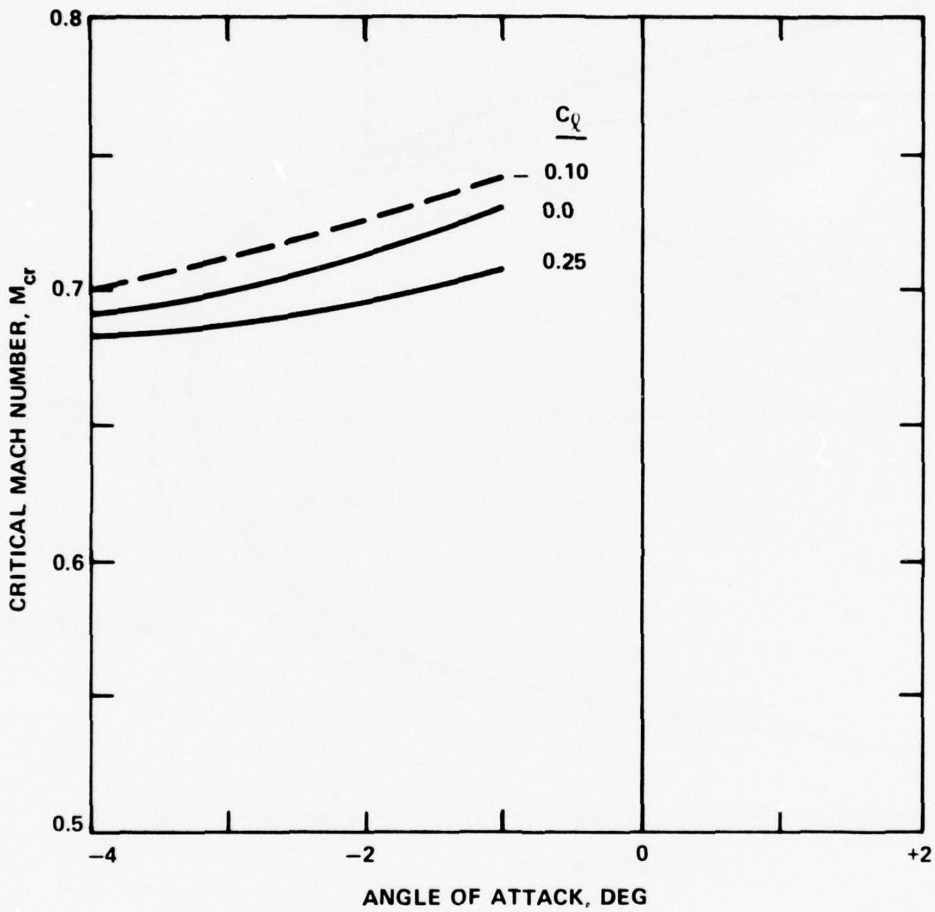

Figure 12 — Predicted M_{cr} for NCCR 1505-7567S

the front half had to be manufactured. The chord line was defined from the uncambered nose-chord line intersection point to the cambered trailing edge-chord line intersection point. Figure 13 shows the profile and corresponding chord line and camber line.

The fourth and fifth CC airfoils of the group were designed without restrictions as to thickness or camber distributions. The design objectives for each airfoil were the previously stated objectives (3) and (5). Each airfoil design was conducted by separate parties working independently, but with the same baseline objectives. This was done to prevent the sort of idea contamination and commonality of design that can result from close interaction. Thus, one aspect of this dual effort was to observe similarities and differences between the two end product airfoil profiles. It is one measure of the design leeway available while satisfying the M_{cr} requirements.

A complete description of the design methodology or intermediate contours used in designing these two airfoils is beyond the scope of this report. Instead, a brief description of the two contours and the rationale behind them will be presented along with predicted M_{cr} values.

NCCR 1513-7559E:

This airfoil was designed by the author to accomplish the stated objectives with the added objective of reducing airfoil pitching moment about the 50-percent chord point. Design conditions of C_ℓ and α were chosen to represent the operating conditions near the rotor advancing blade tip for evaluation of M_{cr}, and around the three-quarter span position on the retreating blade for evaluation of pressure distribution at high C_ℓ. Many combinations of NACA four- and five-digit series camber lines were evaluated on a basic 15-percent-thick elliptical airfoil. These camber distributions, and some others, were examined for various leading edge and trailing edge radii obtained by a local redistribution of the basic elliptical thickness distribution.

The CC airfoil must operate at small negative angles of attack on the rotor's advancing blade tip. Thus, M_{cr} must be evaluated at this

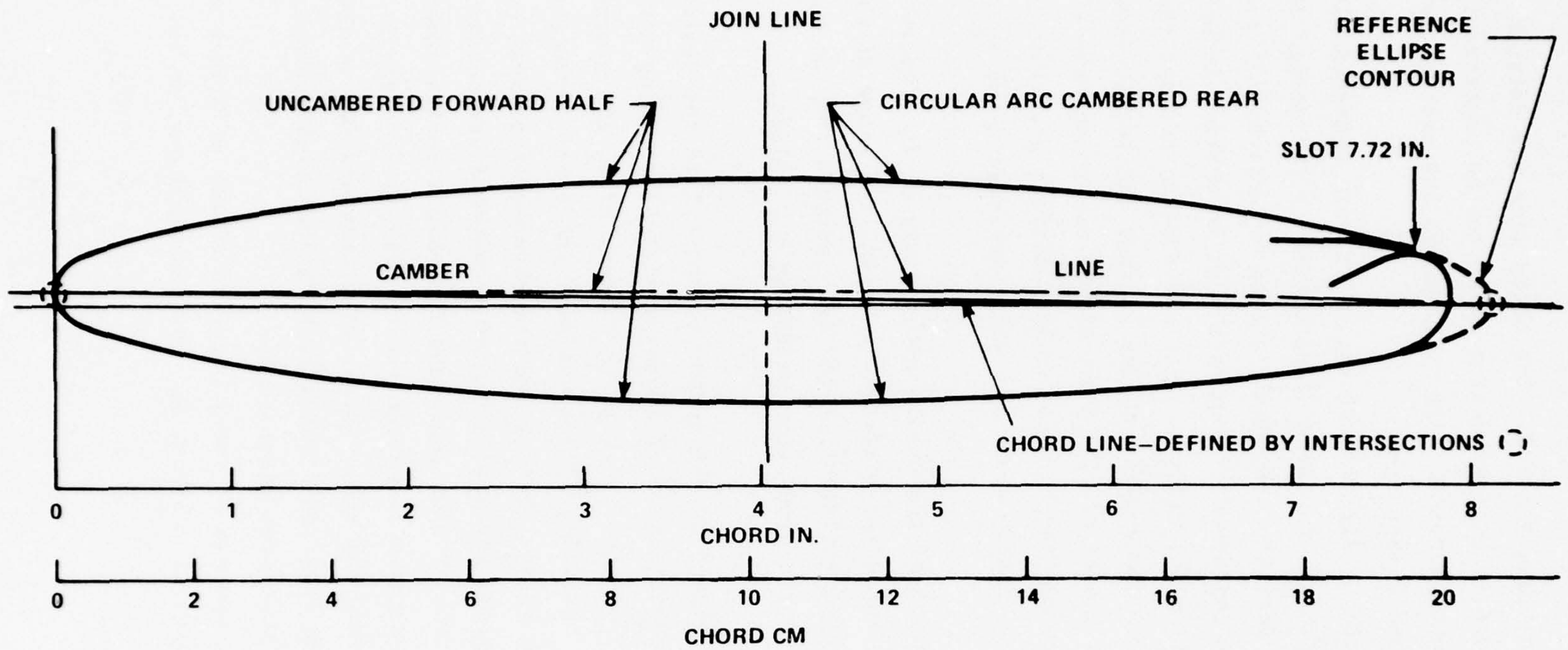

Figure 13 – Airfoil Contour NCCR 1505-7567S

negative angle of attack which induces a leading edge lower surface suction peak. Initial results from the NACA 210 camber line gave improved pitching moments but poor M_{cr} due to strong suction peaks induced on the leading edge lower surface. The final camber line retained the NACA 210 mean line from the nose to five-percent chord, but it was reduced to 90 percent of the original design lift coefficient. A cubic mean line was applied from the five-percent chord back to the trailing edge. The cubic was prescribed by position and slope compatibility at the 210 nose camber junction and by trailing edge position with prescribed slope. The airfoil's basic elliptical thickness distribution was modified to produce larger radii at both the leading edge, $(r/c)_{\ell e} = 0.015$, and the trailing edge, $(r/c)_{te} = 0.020$. The trailing edge surface was obtained by modified thickness distribution, rather than the use of an inserted circular shape, in order to preserve compatibility between the upper surface slot and the trailing edge Coanda surface. The trailing edge is therefore a modified elliptical contour. The resulting profile is shown in Figure 14 along with an expanded view of the somewhat unusual camber line.

NCCR 1610-8054S:

The final airfoil was designed by E.O. Rogers.* Point design conditions of C_ℓ and α were chosen similar to those previously mentioned. The general approach was to vary the geometric properties of the basic ellipse in an attempt to find an improved geometry. As with the other design, simple camber was found to increase the lower surface leading edge suction peak, thus adversely affecting critical Mach numbers. The solution for this design was to minimize camber in the leading edge region, but to retain aft camber for its benefits to augmentation. Moving the camber peak aft (as with a NACA 67 mean line) tends to decrease velocity in the slot region. This has the advantage of avoiding local shock conditions at the blowing jet which can cause jet detachment. Increased nose down pitching moments, a result of the aft camber distribution, was found to be a

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*Reported informally by E.O. Rogers (Design of A Circulation Control Airfoil for Application to Helicopter Rotors, ASED TM 16-76-33, Nov 1975).

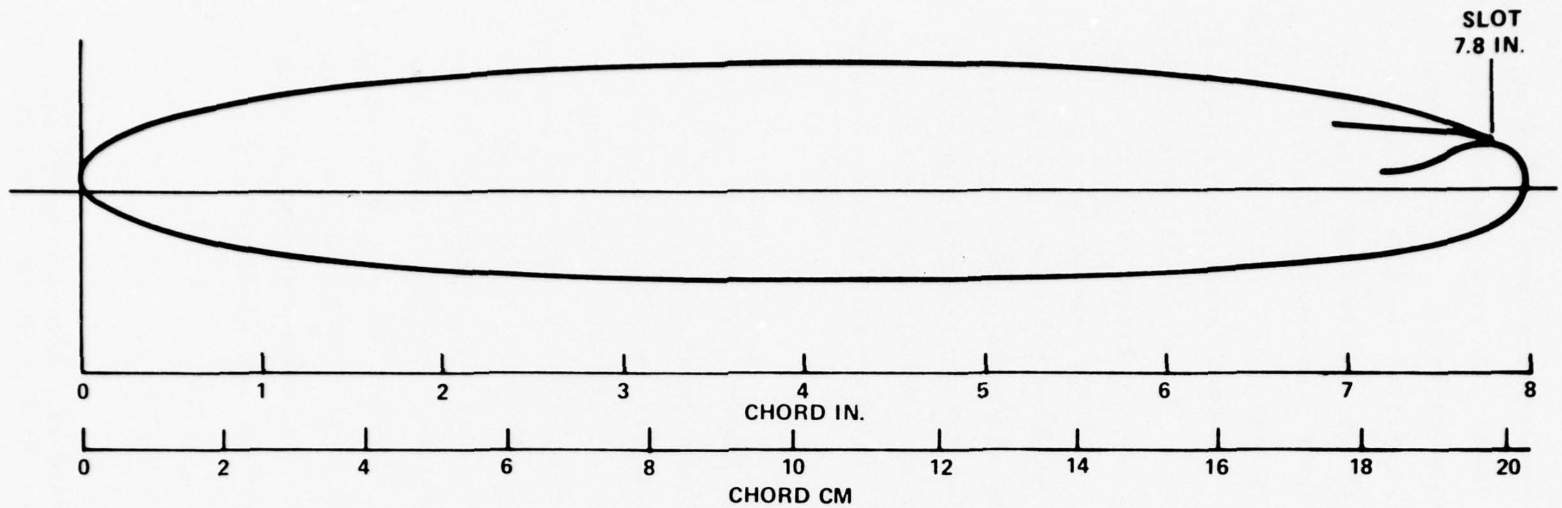

Figure 14a - Airfoil Contour

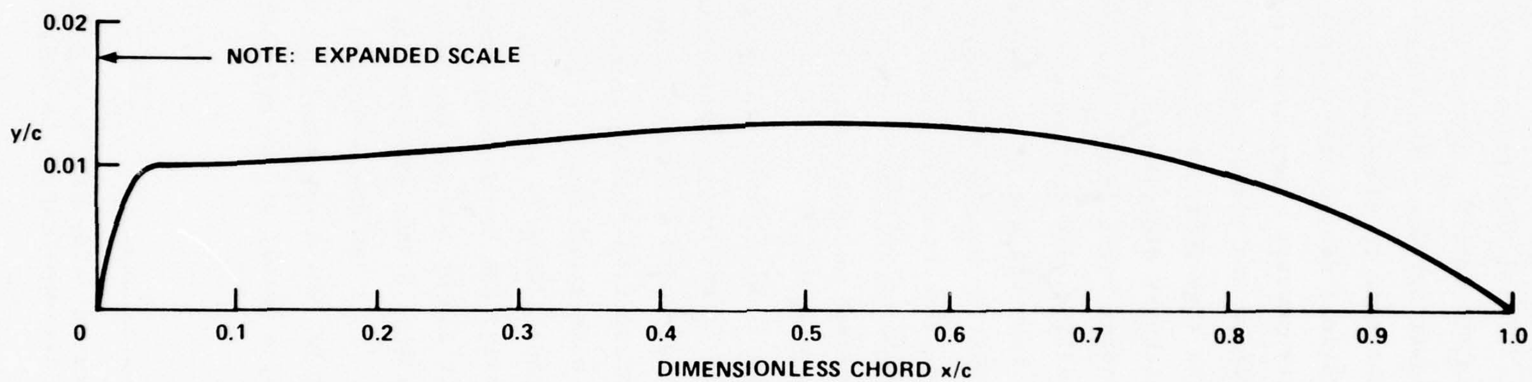

Figure 14b - Camber Distribution

Figure 14 — Airfoil Contour and Camber NCCR 1513-7559E

compromise aspect of the design. Other design features include increased airfoil thickness for better control over the pressure distribution to delay transonic flow, and decreased leading edge radius. The decreased leading edge radius was obtained by a power function redistribution from the pure elliptical profile, which ensured continuity of the surface derivatives. The trailing edge Coanda surface uses a spiral contour (similar to NCCR 1510-7567S, described earlier) which negotiates from r/c = 0.022 just aft of the slot to a maximum value of r/c = 0.40 as it becomes tangent with the lower surface. Figure 15 shows the profile and an expanded view of the camber line.

DESIGN COMPARISON

As previously stated, the objectives for the two airfoil designs were to obtain M_{cr} characteristics similar to the pure ellipse and to maintain the high blowing augmentation characteristics, a combination which had not previously been obtained. Augmentation was ensured by adherence to already established design practices in the trailing edge region. Specifically, both designs incorporated a significant aft camber, even though the forward camber distributions were quite different. Comparison of the expanded airfoil camber lines (Figures 14 and 15) shows nearly identical distributions aft of 88-percent chord. Both designers found that camber line slope near the trailing edge contributed to improved pressure distributions in that region. Secondly, the radius-to-chord ratio on the blown trailing edge region was kept to r/c = 0.20 as a minimum for both airfoils, although the shapes were basically different (one a spiral, the other a modified ellipse).

Predicted pressure distributions are shown in Figure 16 for the two airfoils at their respective critical Mach numbers for $C_\ell = 0.0$ and $\alpha = -4.0$ degrees. At this condition both airfoils show that M_{cr} is established by the lower surface leading edge pressure due to negative angle-of-attack. Upper surface distributions show a gradual development of lift approaching the trailing edge (and then full pressure recovery as required by the

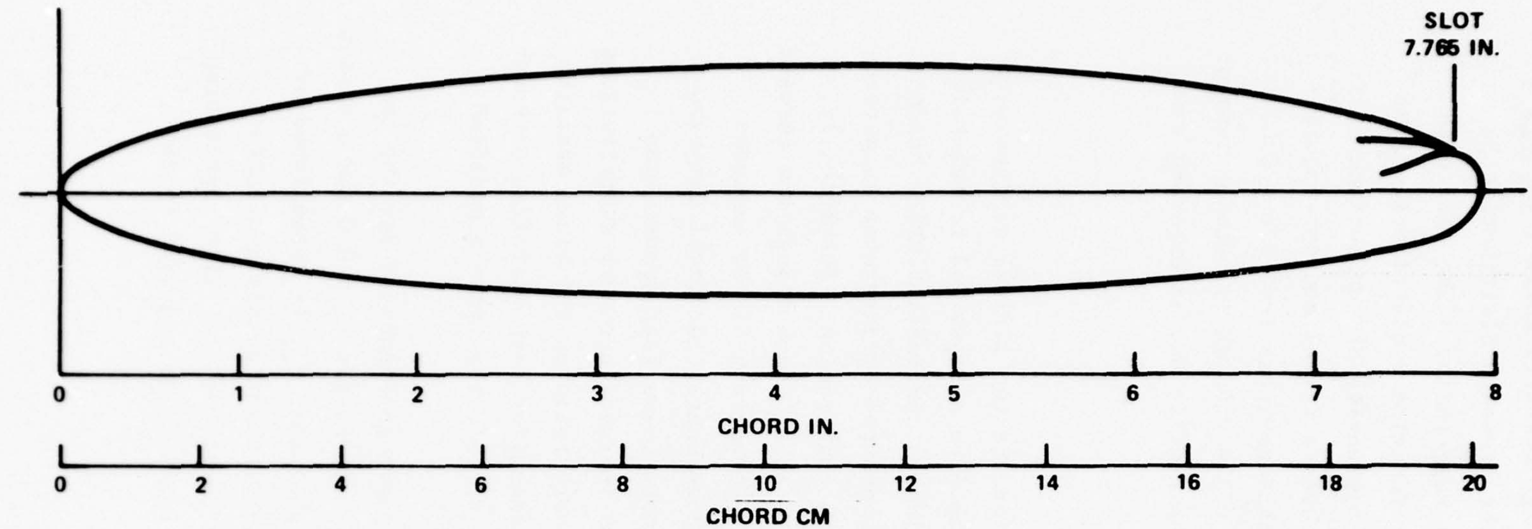

Figure 15a - Airfoil Contour

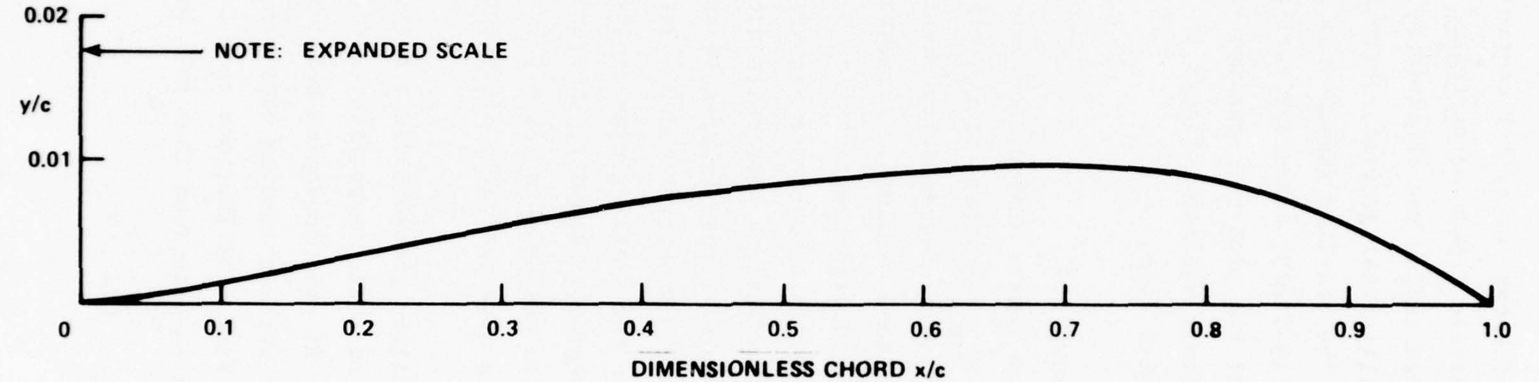

Figure 15b - Camber Distribution

Figure 15 — Airfoil Contour and Camber NCCR 1610-8054S

Figure 16 — Predicted Pressure Distributions at $C_\ell = 0.0$, $\alpha = -4.0$

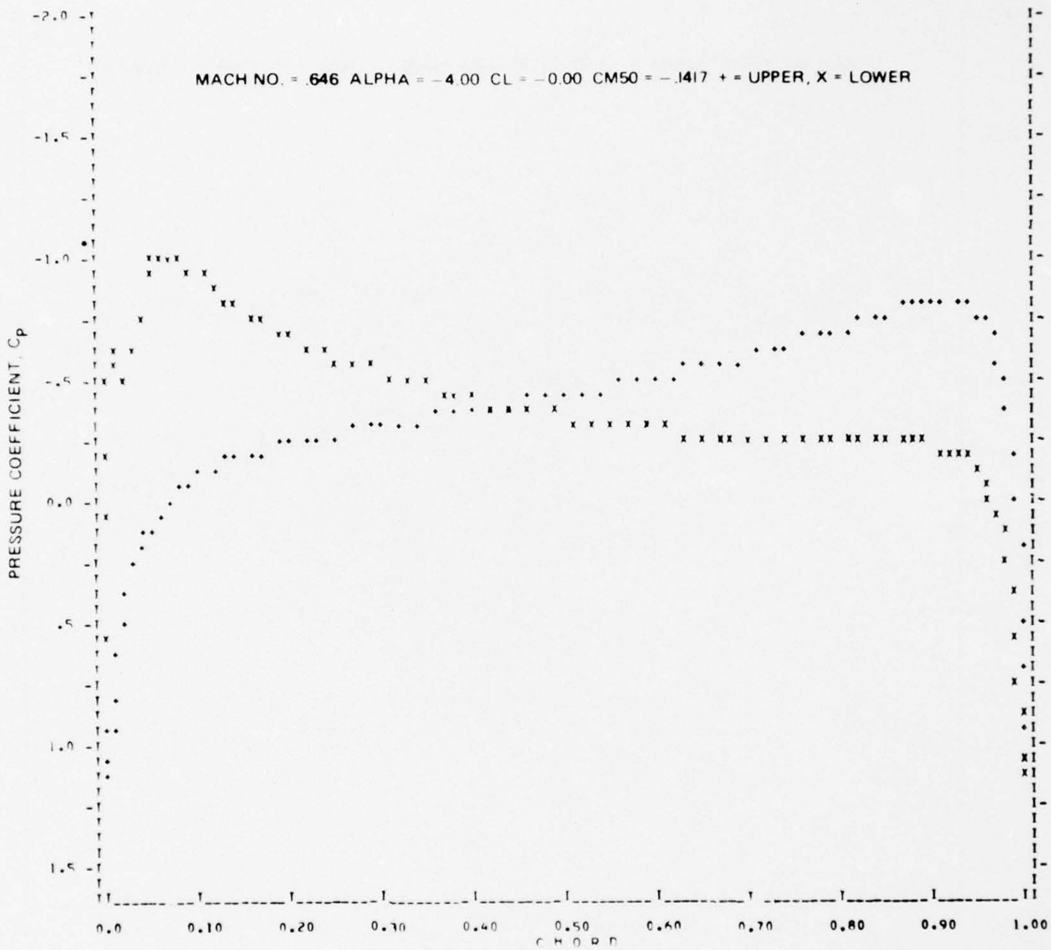

Figure 16a - Airfoil NCCR 1513-7559E

Figure 16 (Continued)

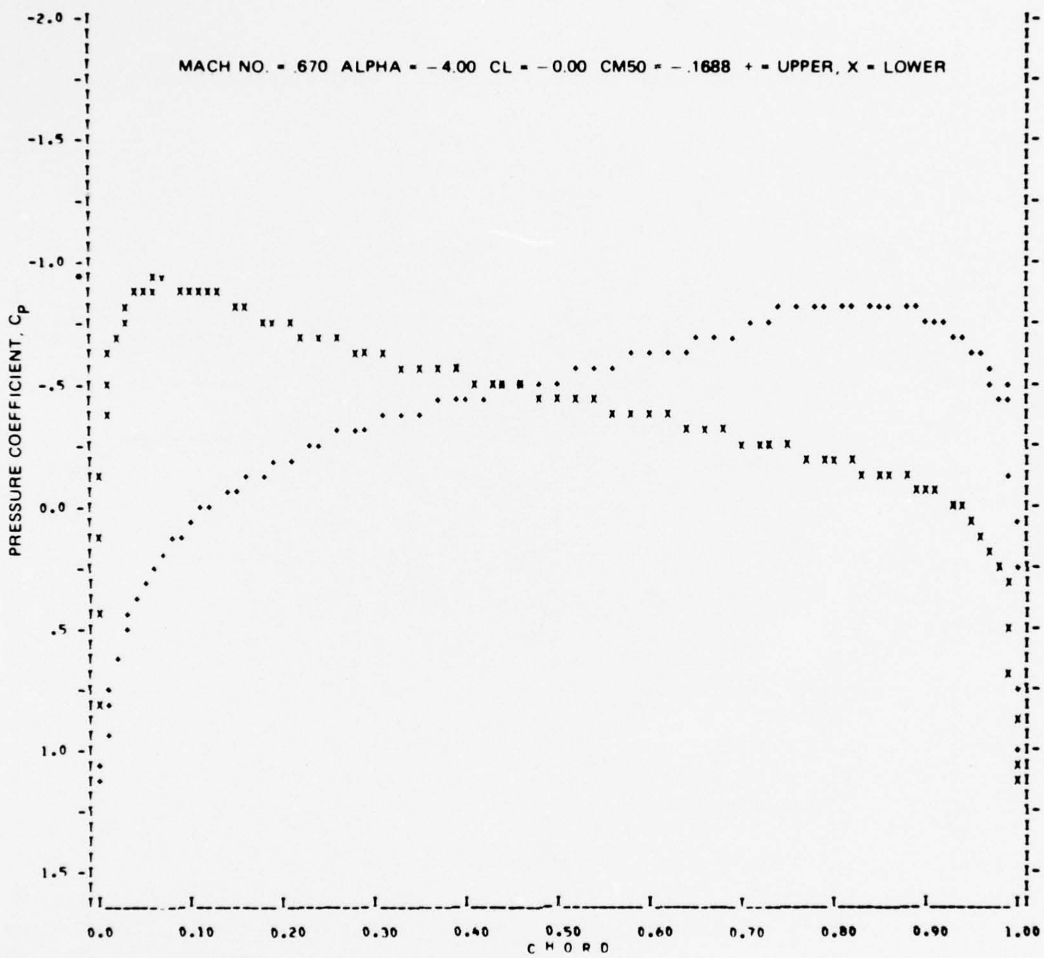

Figure 16b - Airfoil NCCR 1610-8054S

pontential flow analysis). The nose camber of NCCR 1513-7559E produces a slightly stronger value of $C_{p_{min}}$ at the leading edge which gives a somewhat reduced value for critical Mach number. However, the nose camber also induced a more rapid flow acceleration around the nose upper surface, reducing the predicted airfoil pitching moment as intended. Note that both upper surfaces retain a favorable pressure gradient back to about 90-percent chord (just ahead of the blowing slot), and that both lower surfaces are in slightly adverse gradients aft of the pressure peak (beyond about 8-percent chord).

Figure 17 shows another set of pressure distributions for $C_\ell = +0.5$ and $\alpha = -2.0$ degrees. Critical Mach numbers for this condition are established by the upper surface pressures in the airfoil aft regions ahead of the blowing slot. This allows shock down conditions upstream of the injected air when the airfoil is operated above M_{cr}. The nose camber of NCCR 1513-7559E again shows higher local velocities on the leading edge upper surface, contributing to a lower predicted pitching moment for this airfoil than for NCCR 1610-8054S.

The variation of M_{cr} with C_ℓ and α was estimated for both airfoil designs as shown in Figure 18. These estimates show that both airfoil contours will have good M_{cr} characteristics. Contour NCCR 1610-8054S has higher overall values for M_{cr} than contour NCCR 1513-7559E. Comparison of the curves of Figure 18 to those of Figure 4 clearly shows that both airfoil designs should exhibit M_{cr} characteristics similar to those of the pure ellipse NCCR 1500-2480E, rather than the undesirable characteristics of the rounded ellipse NCCR 1500-6083C. When these M_{cr} and augmentation characteristics are validated by airfoil evaluation in the wind tunnel, the airfoils will have fully met the requirements set forth at the time of their design. Incorporation of such airfoils into a new CCR design will then represent significant efficiency gains for the rotor system.

As part of the development program one of these two airfoils was to be evaluated in the DTNSRDC 7- x 10-foot Transonic Wind Tunnel. Airfoil contour NCCR 1610-8054S was chosen due to its better overall M_{cr} map as

Figure 17 — Predicted Pressure Distributions at C_{ℓ} = 0.5, α = -2.0

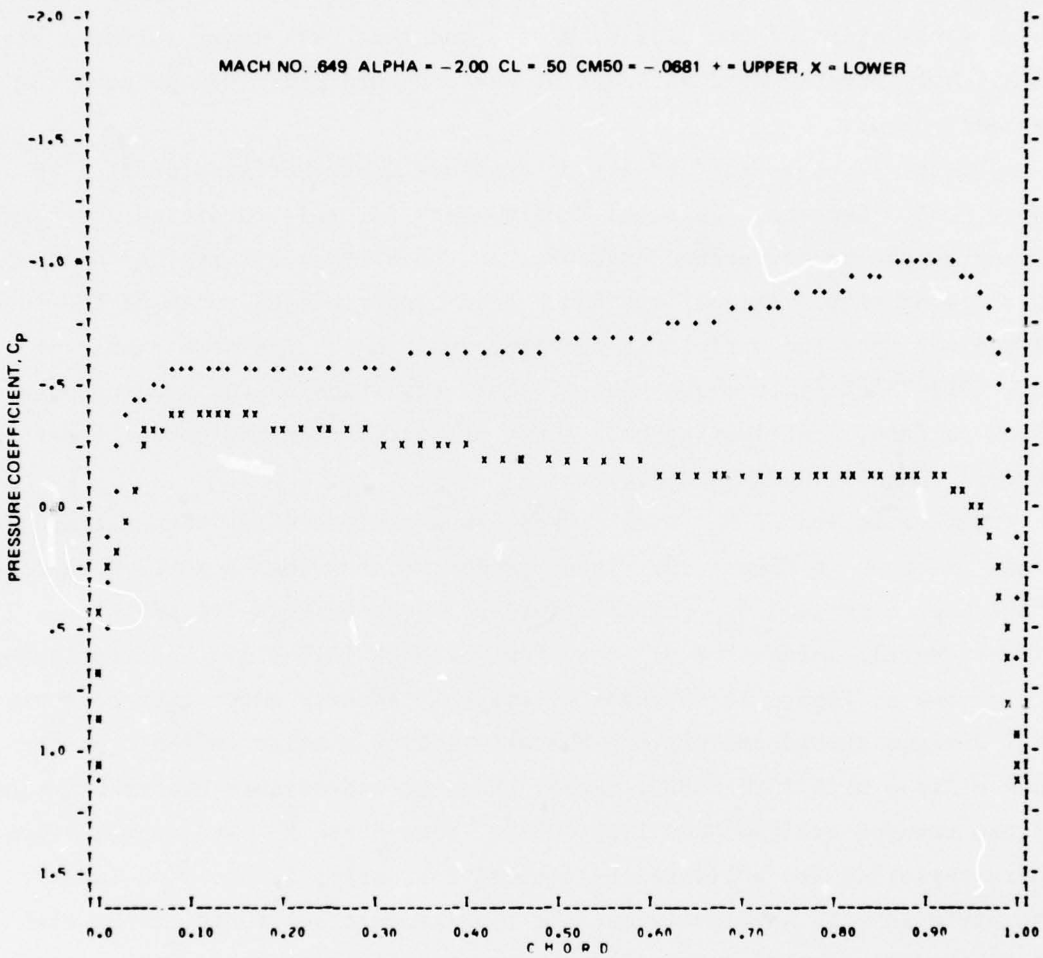

Figure 17a - Airfoil NCCR 1513-7559E

Figure 17 (Continued)

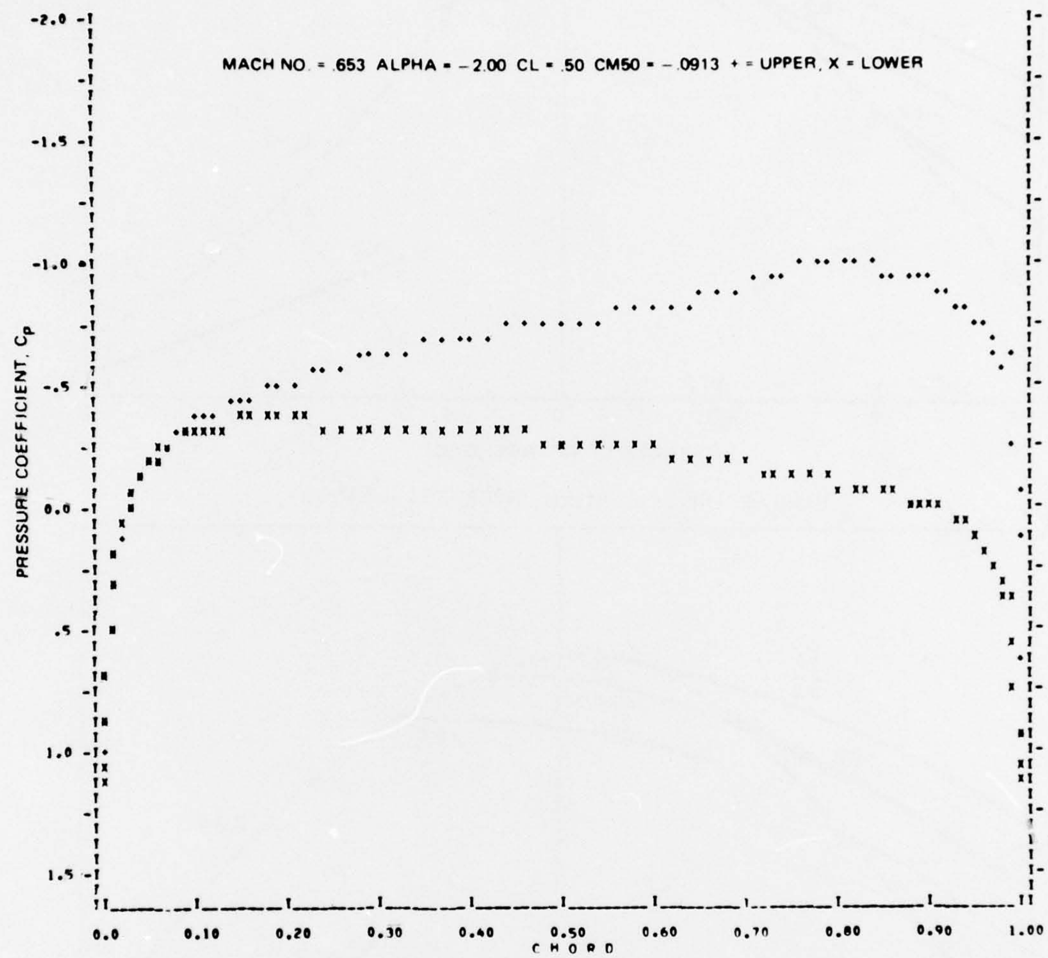

Figure 17b - Airfoil NCCR 1610-8054S

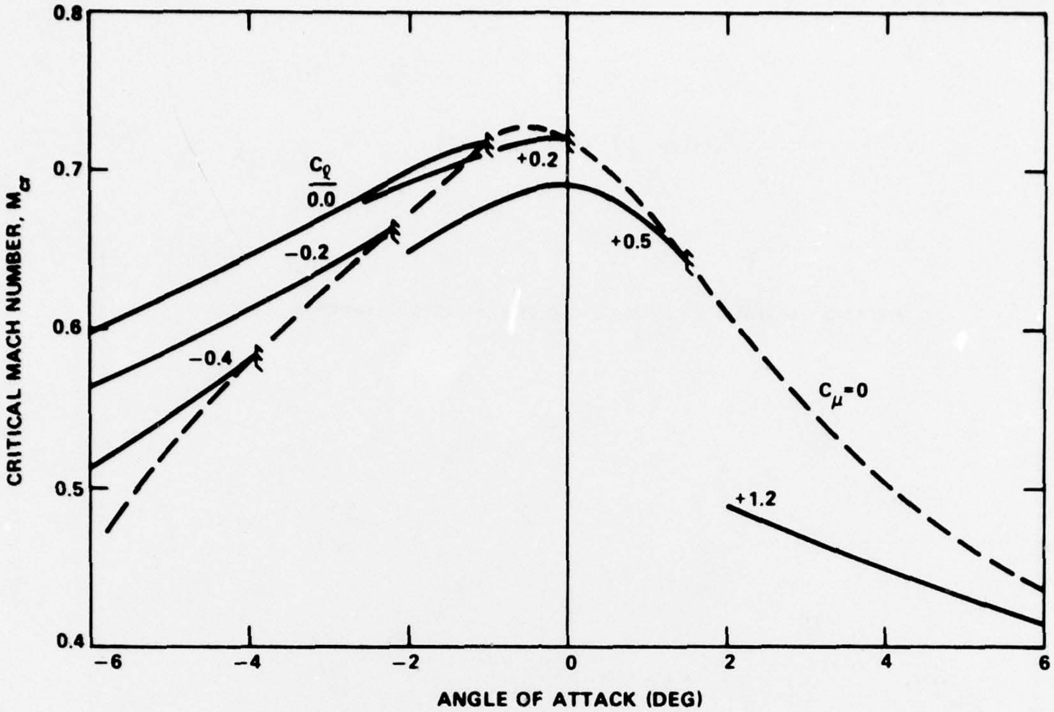

Figure 18a - Contour NCCR 1513-7559E

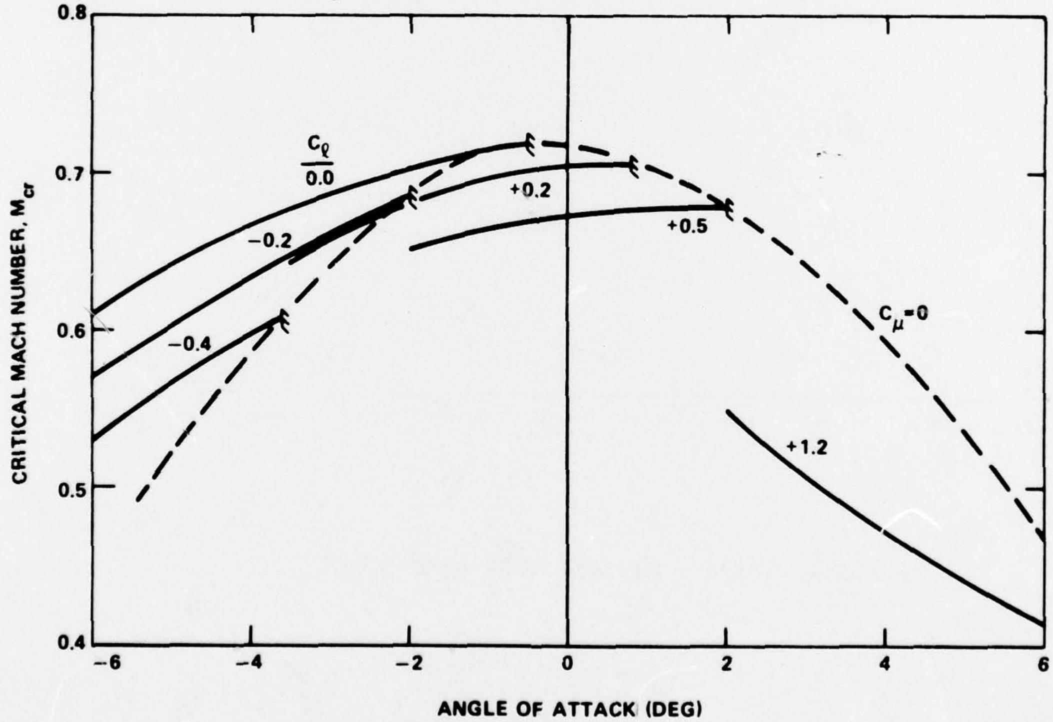

Figure 18b - Contour NCCR 1610-8054S

Figure 18 — Critical Mach Number Map for Designed Airfoils

shown in Figure 18. The two-dimensional airfoil model was designed to span the full 10-foot width of the tunnel and had full span blowing to ensure good two-dimensional flow. The model chord was 18 inches which is full scale chord for the XH2/CCR demonstrator rotor blade. Thus the airfoil test results will be at full scale Mach number and Reynolds number. The wind-tunnel evaluation was performed in August 1976, and the results are currently being analyzed.

SELECTED DATA COMPARISON

A selected portion of the subsonic two-dimensional wind-tunnel data is included in this report for comparative purposes. A complete comparison of the data would, of course, require examination of the lift, drag and pitching moment characteristics over the broad range of α and C_μ. For instance, a leading edge separation (short bubble) may exist at one operating condition, having a pronounced effect on airfoil augmentation, whereas the airfoil may exhibit normal augmentation at other operating conditions. The limited amount of data included in this report is therefore intended only to show general trends of recent airfoil tests relative to the previous data base.

Improved augmentation is one of the long term goals of this airfoil development program, but it was recognized to be one of the most difficult characteristics to evaluate and design. Consequently, the CC airfoil designs concentrated on state-of-the-art augmentation in combination with improved M_{cr} characteristics. Figure 18 has already shown that these airfoils were successfully designed to meet the M_{cr} objectives, being similar in contour to NCCR 1500-2480E. Augmentation and lift characteristics were obtained for each airfoil by subsonic wind-tunnel evaluation of two-dimensional models. Characteristics for some of these airfoils are shown in Figure 19 in comparison to prior CC airfoil characteristics. These lift curves compare favorably with those of contour NCCR 1500-6083C (the baseline for augmentation). Contour NCCR 1513-7559E shows higher C_ℓ values

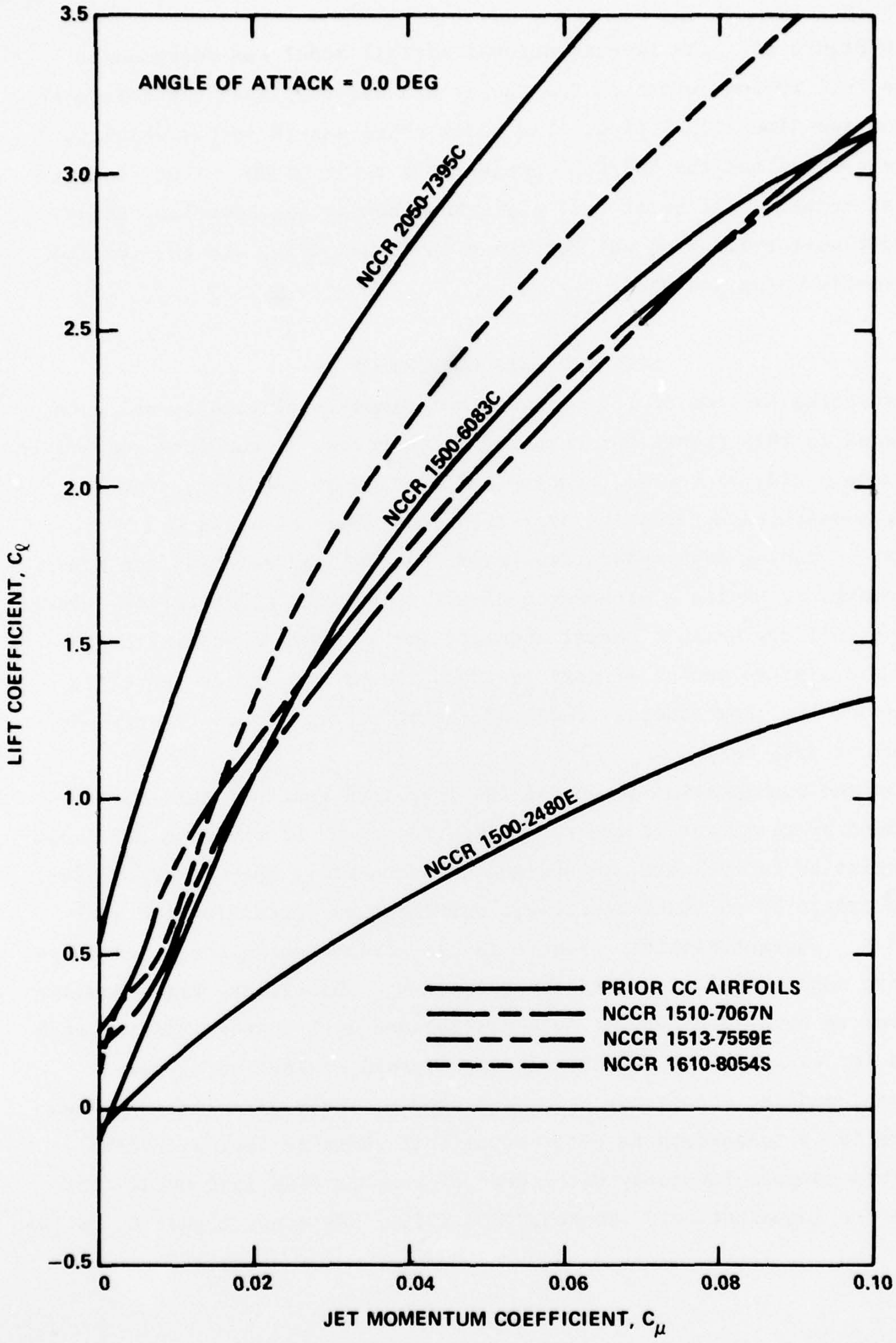

Figure 19 — Comparison of Airfoil Lift Characteristics

in the low C_μ range than the baseline airfoil. This is partly due to the initial C_ℓ from camber, but is sustained by a good augmentation. The net effect is that NCCR 1513-7559E requires much less blowing for a given C_ℓ than does the baseline airfoil over much of its operating range ($C_\ell \leq 1.4$). Contour NCCR 1610-8054S achieved excellent augmentation for $C_\ell \geq 0.7$. It surpassed the C_ℓ curve of contour NCCR 1513-7559E for C_ℓ greater than 1.0 and was consistently better than the baseline airfoil.

Profile drag characteristics are shown in Figure 20 for the designed airfoils and for several prior CC airfoils. The drag curve for contour NCCR 1513-7559E follows fairly closely to the baseline airfoil, NCCR 1500-6083C. However, contour NCCR 1610-8054S, with its higher lift augmentation, shows a much different drag curve indicating a lack of jet thrust recovery. Both the data and wind-tunnel operating conditions will be carefully examined to ensure a proper interpretation of this trend. In general, one may observe that those airfoils with higher lift augmentation have less jet thrust recovery, and those with less augmentation have more thrust recovery.

CC airfoil pitching moment data are shown in Figure 21 as they vary with the airfoil lift coefficient. Airfoil NCCR 1610-8054S closely follows the half-chord pitching moments of the two 15-percent uncambered airfoils (NCCR 1500-2480E and NCCR 1500-6083C). The nose camber of contour NCCR 1513-7559E provides a more positive pitching moment initially (up to $C_\ell = 0.7$) but then deteriorates to values more negative than the 15-percent uncambered airfoils for the angle of attack shown.

The data show that airfoil drag and pitching moment (as well as augmentation) are sensitive to both the specific trailing edge geometry and to the airfoil body contour. The new airfoil designs have incorporated several departures from previous state-of-the-art design practices (i.e., nose camber, extreme aft camber, spiral trailing edge contours, modified thickness distributions, and more aft slot locations). Two-dimensional data from these airfoils will be thoroughly studied and intercompared over the operating envelope to gain an understanding of how these different contours have contributed to the complete picture of airfoil performance.

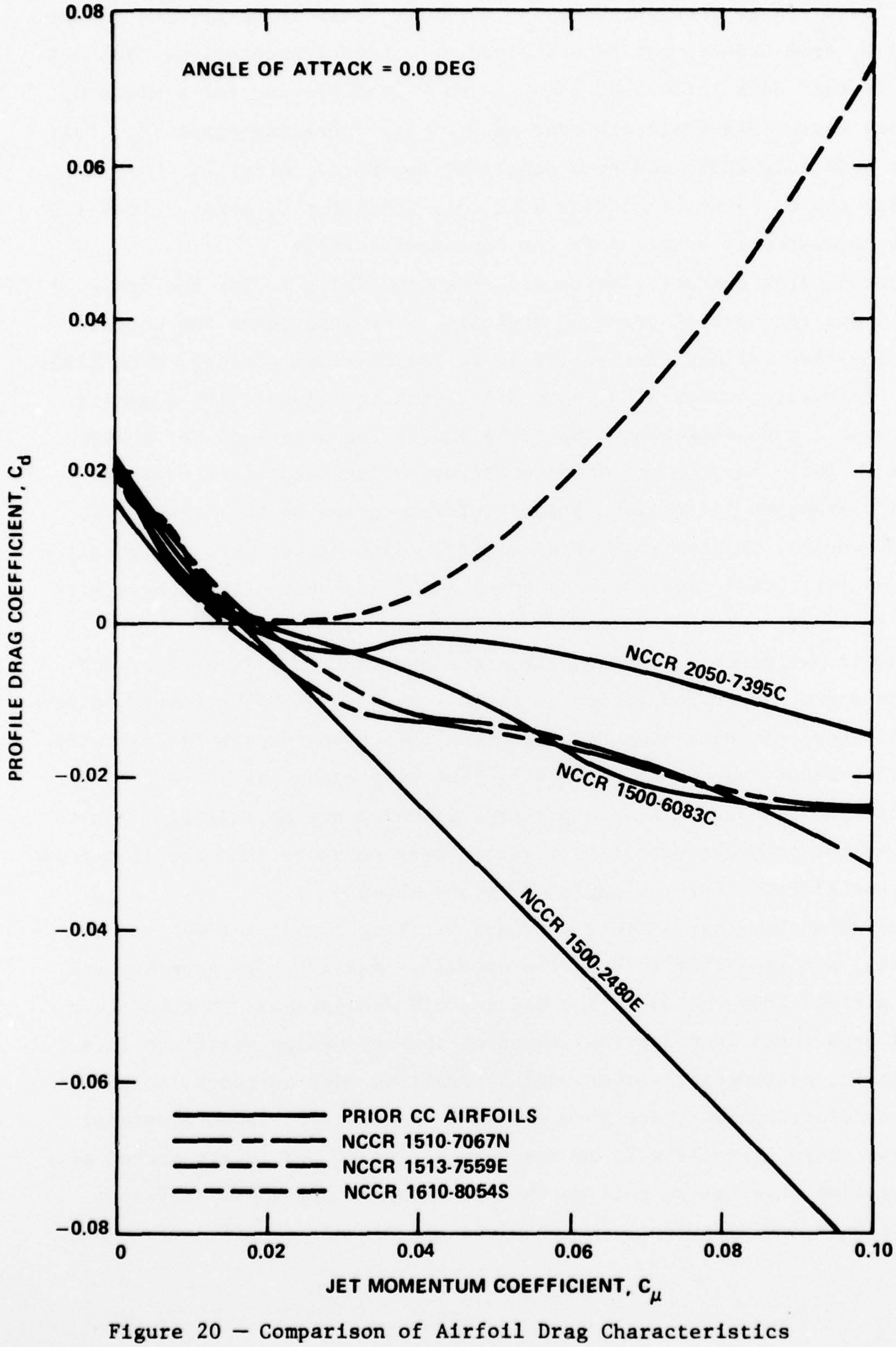

Figure 20 — Comparison of Airfoil Drag Characteristics

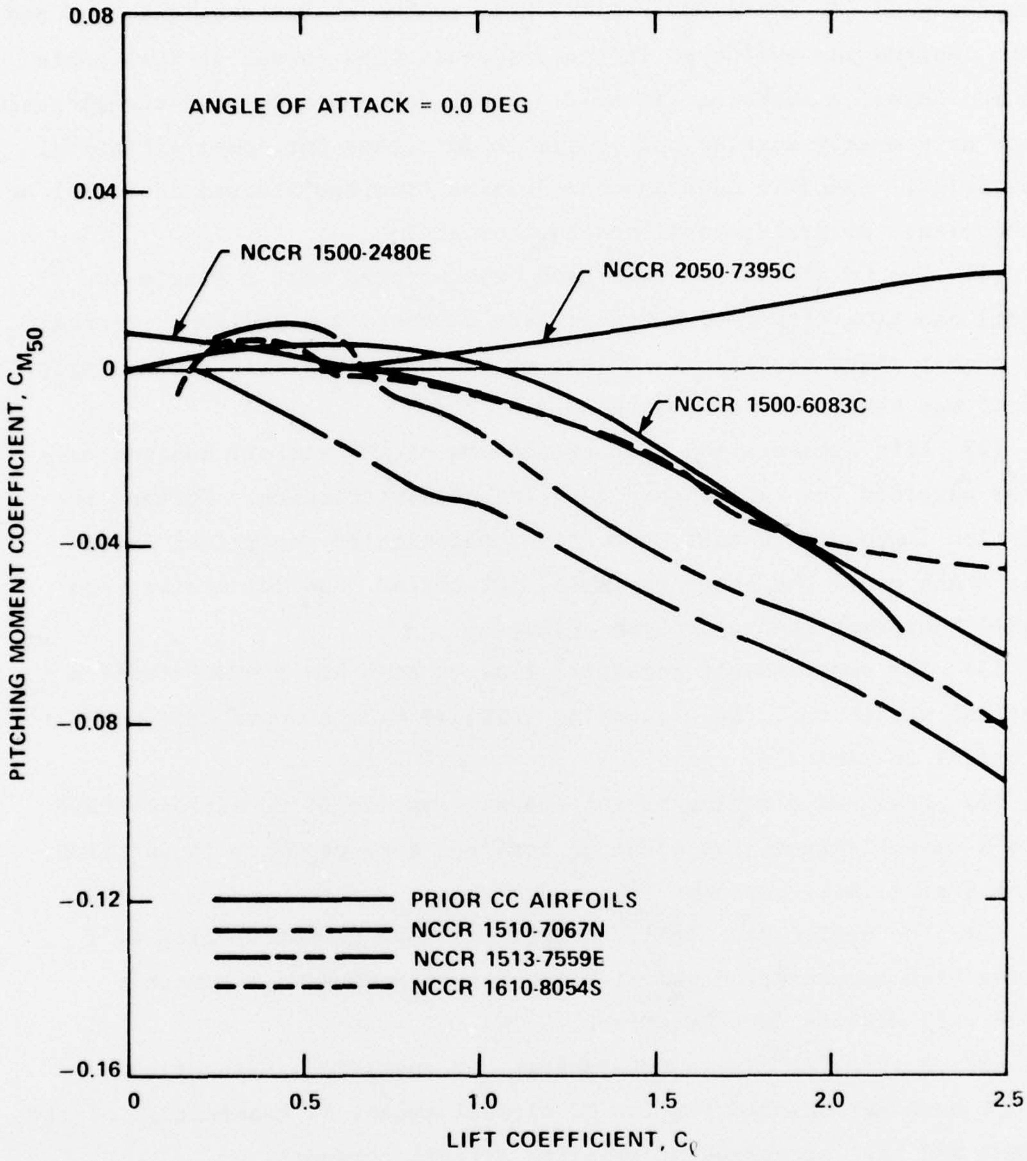

Figure 21 — Comparison of Airfoil Pitching Moment Characteristics

CONCLUSIONS AND RECOMMENDATIONS

As part of the development program five new CC airfoils have been designed and wind-tunnel evaluated. Two of these airfoils were specifically designed for improved critical Mach number characteristics, and one of the designs was evaluated in the transonic wind tunnel at full scale Mach and Reynolds numbers. These transonic and subsonic wind-tunnel evaluations have nearly doubled the available data base for quasi-elliptical CC airfoils. Specific data and conclusions from the amassed data will be forthcoming. Several general conclusions are:

(1) Two CC airfoil designs have demonstrated that a single CC airfoil can have both good subsonic lift augmentation and good critical Mach number characteristics. This combination of qualities in a single airfoil was heretofore nonexistent.

(2) Lift augmentation characteristics of the airfoil designs have met or exceeded the established baseline characteristics. Further augmentation improvements must come from sophisticated analytical design tools which model the boundary layer, jet efflux, and jet mixing; and establish appropriate separation criteria.

(3) The compressible potential flow program has proven itself a practical design tool for evaluating critical Mach numbers of quasi-elliptical CC airfoils.

(4) Drag and pitching moment characteristics of CC airfoils have shown a sensitivity to the specific trailing edge geometry in addition to the airfoil body contour.

(5) The design of a specific trailing edge geometry which will provide high augmentation and high jet thrust recovery at subsonic speeds will require further effort.

(6) A specific design methodology, or specific design criteria, has not been established for the CC airfoil except by examination of the present and past successes of specific airfoil contours.

Continuance of the CC airfoil development program will accomplish the previously stated long term objectives. A sophisticated computer analysis for CC airfoils will soon be ready for implementation. Early application of the analysis, in conjunction with two-dimensional airfoil models, will produce a more thorough understanding of the mechanism behind higher augmentation and higher aerodynamic efficiency. Applications of the analysis will also serve to establish better analytical capabilities in these areas for future CC airfoil designs.

The end product of this airfoil development is not the airfoil per se, but a highly efficient, low maintenance, low vibration CCR helicopter rotor system. Knowledge gained from the program may apply equally well to the needs of high lift fixed wing applications (Circulation Control Wing) or to high speed slowed and stopped rotor systems (X-Wing). The airfoil characteristics of high augmentation, high aerodynamic efficiency, and good critical Mach number each contribute to rotor efficiency. Improved CC airfoil contours will be used to design new circulation control rotors in a continuing effort to assess potential performance and to provide higher efficiencies for the low maintenance CCR helicopter rotor system.

ACKNOWLEDGMENT

The author would like to recognize the following individuals for their participation and contributions to the program reported herein.

- J.S. Abramson for performing the five subsonic wind tunnel investigations and for assistance in coordinating the model construction and evaluation schedules.
- E.O. Rogers for designing airfoil NCCR 1610-8054S and for assistance in the evaluation of M_{cr} characteristics for several other designs.
- P.S. Montana for overall assistance in the transonic wind tunnel airfoil investigation.
- A.P. Clark and A.A. Rok for structural design of the transonic airfoil model and for overseeing the construction stage.
- S.M. Gottlieb, W.B. MaGuire, D.R. Chaddock and F.R. Ridley for assistance in the transonic wind tunnel investigation from concept through data reduction.

REFERENCES

1. Dunham, J., "Circulation Control Applied To A Circular Cylinder,' Nat. Gas Turbine Est. (England) Report R. 287 (Jul 1967).

2. Kind, R.J., "A Proposed Method of Circulation Control," Ph.D. Dissertation, University of Cambridge, England (1967).

3. Cheeseman, I.C. and A.R. Seed, "The Application of Circulation Control by Blowing to Helicopter Rotors," J.R. Ae.S., Vol. 71, No. 848 (Jul 1966).

4. Williams, Robert M. and R.A. Hemmerly, "Determination of the (Ideal Practical) Hover Efficiency of Circulation Control Rotors," NSRDC Technical Note AL-212, AD 902-068L (Aug 1971).

5. Wilkerson, Joseph B., "Design and Performance Analysis of a Prototype Circulation Control Helicopter Rotor," NSRDC Technical Report ASED 290 (Mar 1973).

6. Wilkerson, Joseph B. et al., "The Application of Circulation Control Aerodynamics to a Helicopter Rotor Model," Paper 704, 29th Annual National Forum of the American Helicopter Society, Wash., D.C. (May 1973).

7. Wilkerson, J.B. and D.W. Linck, "A Model Rotor Performance Validation for the CCR Technology Demonstrator," Paper 902, 31st Annual National Forum of the American Helicopter Society, Wash., D.C. (May 1975).

8. Reader, K.R. and J.B. Wilkerson, "Circulation Control Applied To A High Speed Helicopter Rotor," Paper 1003, 32nd Annual National Forum of the American Helicopter Society, Wash., D.C. (May 1976).

9. Williams, R.M. et al., "X-Wing: A New Concept In Rotary Wing VTOL," Paper presented at the American Helicopter Society Symposium on Rotor Technology (Aug 1976).

10. Englar, R.J. et al., "Circulation Control - An Updated Bibliography of DTNSRDC Research and Selected Outside References," DTNSRDC Report 77-0076 (Aug 1977).

11. Paglino, Vincent M., "The Potential Benefits Of Advanced Airfoils for Helicopter Applications," SER-50858, Contract N00019-73-C-0225 (Mar 1974).

12. Englar, R.J., "Two-Dimensional Transonic Wind-Tunnel Tests of Three 15-Percent Thick Circulation Control Airfoils," DTNSRDC Technical Note AL-182 (Dec 1970).

13. Englar, R.J., "Two-Dimensional Subsonic Wind-Tunnel Tests of Two 15-Percent Thick Circulation Control Airfoils," DTNSRDC Technical Note AL-211 (Aug 1971).

14. Rogers, E.O., "Critical Mach Numbers of Circulation Control Airfoils as Determined by Finite-Difference Methods," DTNSRDC Technical Note AL-273 (Aug 1972).

15. Clark, Albert P., "Design Of A Circulation Control Airfoil Model for Evaluation In the Transonic Wind Tunnel," DTNSRDC CID Report 77-1 (Mar 1977).

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